SIM Report No. 12

Scientific Investigations in Micronesia
1949-

# Preliminary Report on the Geology and Marine Environments of Onotoa Atoll Gilbert Islands

by Preston E. Cloud, Jr.

Pacific Science Board
National Research Council
N7-onr-291: T O IV & Viking Fund Inc.

SCIENTIFIC INVESTIGATIONS IN MICRONESIA

operates with finanacial assistance from
Contract N7-onr-291, Task Order IV
between

THE OFFICE OF NAVAL RESEARCH

and

THE NATIONAL ACADEMY OF SCIENCES

SIM has developed as a successor to the former CIMA project with an enlarged scope that includes field research in the physical,biological, and life sciences. Field work under SIM has been conducted in Guam, American Samoa, and in the islands of the Trust Territory in Micronesia since 1949 with transportation and facilities contributed by the Department of the Navy. The field research has been carried out in co-operation with universities, museums, research institutions, and Government agencies under this project of the Pacific Science Board of the National Research Council, supported by the Office of Naval Research and aided by financial assistance from the Viking Fund and other private sources.

# Preliminary Report on the Geology and Marine Environments of Onotoa Atoll, Gilbert Islands

SCIENTIFIC INVESTIGATIONS IN MICRONESIA

Pacific Science Board

National Research Council

Preston E. Cloud, Jr.
U. S. Geological Survey
Washington, D. C.
June 1952

ACKNOWLEDGMENTS

This report presents preliminary results of geological field work done in 1951 under the Atoll Project of the National Research Council's Pacific Science Board. The project is supported by funds granted to the National Academy of Sciences by the Office of Naval Research, and the field work was carried out with the active assistance of the U. S. Navy Department, Coast Guard, and Army. Special thanks are due for help received from Mr. Harold Coolidge, Miss Ernestine Akers, and Mrs. Lenore Smith, of the Pacific Science Board, and from Lt. M. E. Katona and Ens. Lee Nehrt, of the U. S. Coast Guard cutter "Nettle." My associates in the field were Dr. E. T. Moul, Dr. W. H. Goodenough, Dr. A. H. Banner, Mr. D. E. Strasburg, and Mr. John Randall.

The field work of the Onotoa Party being in the Gilbert and Ellice Islands Colony, we were the guests of the British Government, then represented by Acting Resident Commissioner R. J. Keegan, who took a most helpful personal interest in our work. Special courtesies and favors were also received from Mr. B. C. Cartland, Mr. Stanley Silver, and Mr. Alan Hart, of the Tarawa Government staff.

The then Colony Lands Commissioner and Administrative Officer on Onotoa, Mr. Richard Turpin, and his wife befriended and helped the entire field party in every conceivable way--to have them as "guardians" was a great help in carrying out our work among a people whose language and ways were remote from ours.

Finally, I must thank the people of Onotoa themselves, who welcomed us to their island and helped us as much as they could.

CONTENTS

Page

# ILLUSTRATIONS

## Tables



## Figures

ILLUSTRATIONS

Plates

1. [illegible]
2. [illegible]
3. [illegible]
4. [illegible]
5. [illegible]

Figures

1. Index map, [illegible]
2. Generalized [illegible]
3. [illegible]
4. [illegible]
5. [illegible]
6. [illegible]
7. [illegible]
8. [illegible]

PRELIMINARY REPORT ON THE GEOLOGY AND MARINE ENVIRONMENTS OF ONOTOA ATOLL, GILBERT ISLANDS 1/

By Preston E. Cloud, Jr. 2/

---

1/ Publication authorized by the Director, U. S. Geological Survey.

2/ Geologist, U. S. Geological Survey.

---

## ABSTRACT

Onotoa is a "dry" atoll just south of the equator and west of the international date line. Its yearly rainfall averages only about 40 inches, droughts occur periodically, and ground cover vegetation is sparse. Island deposits are almost exclusively unconsolidated calcium carbonate gravel and sand, the gravel mainly toward the sea and the sand mainly lagoonward. Within this permeable material and the permeable reef-rock beneath, ground water floats in hydrostatic balance with sea water below. Toward the center of islands more than about 1000 feet wide this water is generally potable. In narrower parts of islands, however, it becomes brackish at times of drought, resulting in the death of breadfruit, taro, and even coconut trees. Soils are simply the calcium carbonate sediments, with a humus layer not exceeding about 10 inches and an average pH of about 8.1.

The shape of the lagoon bottom is derived from echo sounding and direct observation. It comprises three shallow basins (maximum depth 8 fathoms) that are separated from one another and from the sea beyond by still shallower water, the whole with numerous small patch reefs that rise to or near the surface. The near-surface framework of the Onotoa reefs consists primarily

of the blue alcyonarian <u>Heliopora</u>, a genus that is not extensively developed there among now living corals. Fish are shown to be important in the production of lagoonal sediments.

The sediments, soils, and surface waters of the island areas of Onotoa, and the ecologic zones and deposits of its shallow marine waters, are here provisionally described and classified. Preliminary identifications of coral collections indicate them to include about 26 genera and 50 to 60 species.

Limited observations on the chemistry and movement of some of the shallow marine waters show a diurnal variation in pH and an out-flowing gravity current across the windward reef flat and upper benched reef slope. During the day pH rises and precipitation of $CaCO_3$ probably occurs in very shallow waters. At night pH falls, favoring solution of $CaCO_3$ in intertidal environments. Dominance of solution effects in the shore zone is believed to result from constant flushing of precipitated products. The out-flowing gravity current is believed an important factor in origin of offshore grooves and surge channels, through abrasion by debris in transit seaward at times of bench truncation.

It is argued that blue-green sediment-binding and lime-precipitating algae are important in formation of beachrock, presumably both through bonding of successive surface layers and through interstitial precipitation of $CaCO_3$.

Atoll islands are built on sufficiently wide reef foundations at or near the surface of the sea at a distance from the reef front determined by local force of storm waves and to a width determined by time and supply of sediment. First a gravel ridge or rampart is erected by storm waves on the reef flat. On the lagoon side of this gravel rampart the sandy portions of the islands

grow by longshore drift of reef flat debris and by wind action. Erosion occurs mainly at times of storm by breaching or complete removal of islands.

Onotoa provides additional evidence in support of the now well-documented 6-foot eustatic fall of sea level that began probably more than 4000 and less than 7000 years ago. The evidence consists of elevated *Heliopora* flats and elevated cobble stripes such as are known to form only on the reef flat. The superficial appearance of modern reef surfaces in the tropical belt is attributed primarily to whether they were within 6 feet of sea level when this recession began.

## INTRODUCTION

This report presents some of the preliminary results of an integrated program of field studies on the terrestrial and marine botany and zoology, geology, and anthropology of Onotoa (Ō nō' tō ȧ), a "dry" atoll in the southern Gilbert Islands (the Kingsmill Group of early records). These studies were made by a field team of the Pacific Science Board during late June, July, and August of 1951.

The Gilbert Islands (fig. 1) straddle the equator just west of the international date line, and the position of the anchorage at the west side and toward the north end of Onotoa was determined by Ens. Lee Nehrt of USCGC "Nettle" as 1°47'33" S., 175°29'30" E. (U. S. Hydrographic Office, 1950, p. 51, states "northwestern end in 1°46' S., 175°30' S."). Onotoa is the most southerly atoll of the group, though two "reef islands" (Tamana and Arorae) lie still farther south.

Operations were carried out from a temporary base camp adjacent to the Government Station on the more northerly of the two main islands of Onotoa (fig. 2). Materials and equipment for camp and technical operations were assembled at Kwajalein and transported to Onotoa by the U. S. Coast Guard Cutter "Nettle," under command of Lt. M. E. Katona.

All botanical names used in this report were supplied by Dr. E. T. Moul and represent either his provisional field identifications or my extensions of them. All titrations for salinity factors were made and computed in the field by Mr. D. E. Strasburg, my assistant in the geologic field studies. Preliminary identifications of corals were provided by Dr. J. W. Wells, of arthropods by Dr. F. A. Chace, and of mollusks by Dr. H. A. Rehder and Mr. R. T. Abbott.

## GENERAL SETTING AND CLIMATE

The general setting of Onotoa with reference to currents, winds, and geography is shown in figure 1. This atoll lies between the west-flowing south equatorial current and the east-flowing equatorial countercurrent. A local north-flowing current is suggested by the fact that during our stay there a marked swell from the south produced strong surf on exposed lee reefs that face the south (fig. 2). At the same time surf was weak along the stretch of lee reef north from the anchorage around the north end of the atoll to the large northern island (fig. 2).

According to the map on which figure 1 was based, Onotoa lies at about the northern limit of the southeast trade winds. During late June, July, and August of 1951 the wind blew almost steadily from a little south of east to nearly due east, with the exception of recurrent winds from the west on June 24 and 25 and of occasional squalls from the southeast to south-southeast. On one occasion winds of gale or near-gale velocity blew intermittently from the east and southeast for the better part of a day. The British Colonial Office (1950, p. 39) has reported that "For most of the year there is a steady easterly trade wind, but from October to March...occasional west and northwest gales occur. The wind in these gales does not reach hurricane force." An exception to the rule is found in the record of a hurricane at Butaritari in the northern Gilberts, variously dated as December 1927 and January 1928 (Sachet, in Pac. Sci. Bd ., 1951, pp. 8-9).

The climate of Onotoa is warm and even. For the Colony as a whole, the British Colonial Office (1950, p. 39) reports a temperature range of 80° to 90° by day, with a minimum of 70° at night. Our party maintained no systematic

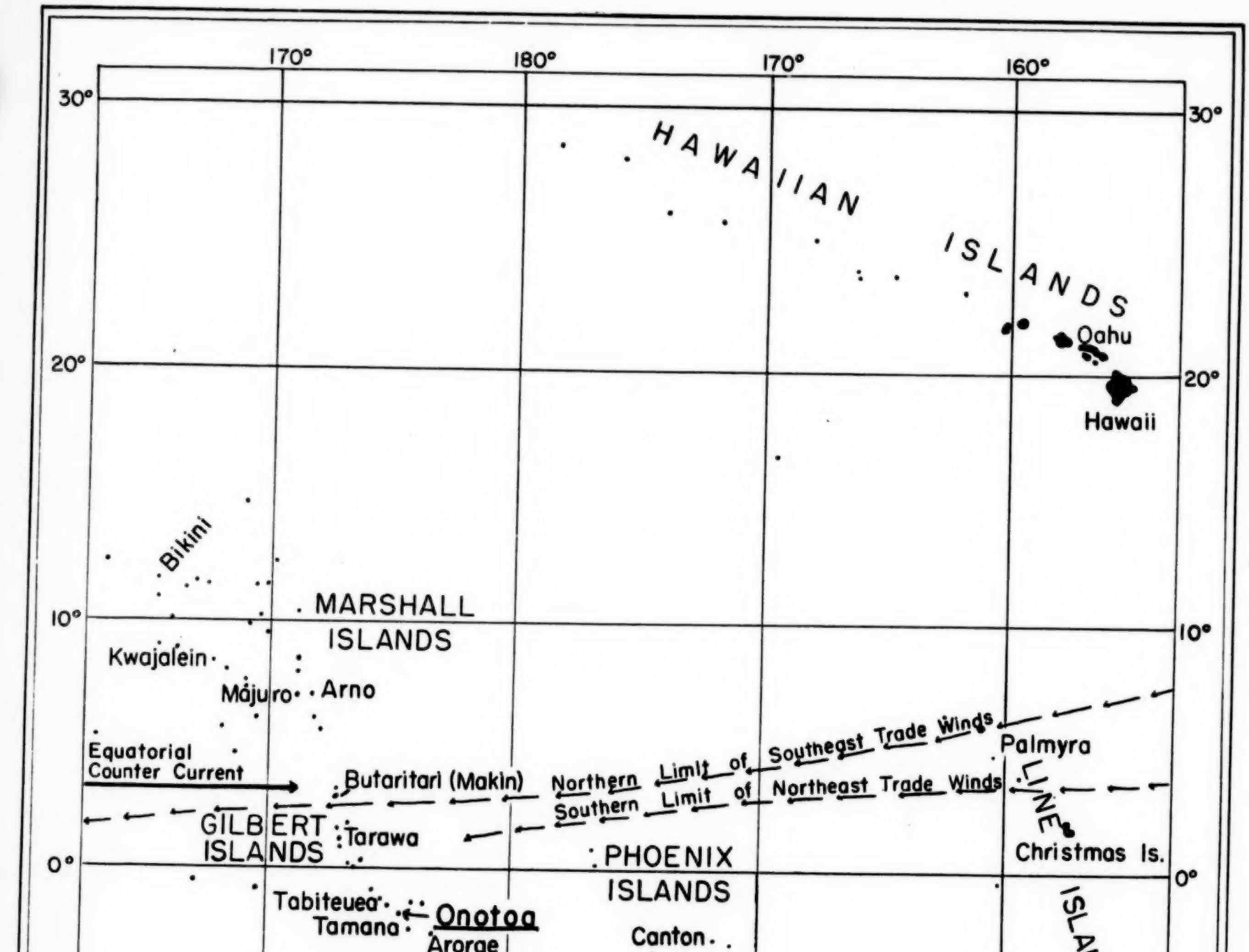



FIGURE I. INDEX MAP, SHOWING LOCATION OF ONOTOA
(From National Geographic Society, map of "Pacific Ocean", Sept. 1943.)

records of air temperature, but I observed a midday high of 87° to 90° F. between noon and 3 p.m. on several occasions in July and August, and on one occasion the midday temperature stood at a low of 76° F. following a period of gale and near-gale velocity winds. At night the temperature fell into the 70's, to as low as 72° between midnight and 5 a.m.

A summary of rainfall data for the Colony as a whole is given by the British Colonial Office (1950, p. 39) as follows:

> "Rainfall varies considerably, not only between the islands, but also from year to year. In an average year the annual rainfall ranges from 40 inches in the vicinity of the equator to 100 inches in the extreme northern Gilberts, with something around 120 inches in the Ellice Islands. In the Phoenix Islands between 40 and 60 inches is a good year's figure, while the Line Islands' rainfall varies from 30 odd inches at Christmas Island to 150 or more at Washington Island. Ocean Island, the central and southern Gilberts, the Phoenix Islands and Christmas Island are subject to severe droughts lasting many months, when the annual rainfall may fall to less than 20 inches. These droughts are said to have a rough cycle of about seven years. In normal years the wettest months are December to February and the driest from August to October."

About 40 inches may be taken as a round figure for the average annual rainfall of Onotoa. Rainfall records locally available were kept at the Government Station on the northern main island by Gilbertese technicians for 1938 and from January 1944 through August 1951 (table 1). These show an average of 44.2 inches per year. The yearly average for the period 1924 to 1930 was 38 inches, according to E. H. Bryan, Jr. (Pac. Sci. Bd., 1951, p. 2). Available records from 1924 through 1934 led Miss Sachet (Pac. Sci. Bd., 1951, p. 16) to an annual estimate of 34.41 inches. The records of table 1 show 1946 as the wettest year, with 85.1 inches, and 1950 as the driest, with only 6.6 inches.

January averages the wettest month, with 8.6 inches, and October the driest, with 1.3 inches. The wettest month on record was January 1949, with 25.4 inches, and zero rainfall has been recorded for every month in the year except July, August, September, and November. In 1950 no rain at all was recorded from January 1 through June.

| | January | February | March | April | May | June | July | August | September | October | November | December | Total Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1938 | 1.18 | 0.04 | 1.54 | 0.13 | 1.45 | 1.77 | 1.87 | 1.82 | 3.44 | 2.81 | 2.27 | 0.75 | 19.1 |
| 1944 | 12.40 | 0.19 | 2.73 | 2.75 | 0 | 4.58 | 3.40 | 3.09 | 2.31 | 0.76 | 6.10 | 0 | 38.3 |
| 1945 | 1.20 | 0 | 0.29 | 1.05 | 2.88 | 8.61 | 5.61 | 2.59 | 1.08 | 0.58 | 3.50 | 0 | 27.4 |
| 1946 | 2.46 | 2.78 | 3.93 | 9.68 | 6.94 | 12.53 | 8.33 | 8.21 | 5.94 | 3.61 | 1.92 | 18.76 | 85.1 |
| 1947 | 16.06 | 0.23 | 0.53 | 0.56 | 1.22 | 3.32 | 0.49 | 1.26 | 0.17 | 0 | 3.21 | 3.46 | 30.5 |
| 1948 | 11.40 | 20.51 | 8.62 | 13.72 | 7.97 | 5.42 | 2.32 | 1.53 | 0.95 | 1.43 | 3.34 | 22.29 | 99.5 |
| 1949 | 25.37 | 4.85 | 3.90 | 0.89 | 3.76 | 1.50 | 2.34 | 0.98 | 0.97 | 0.91 | 0.23 | 0.24 | 45.9 |
| 1950 | 0 | 0 | 0 | 0 | 0 | 0 | 1.80 | 2.76 | 0.80 | 0 | 0.43 | 0.77 | 6.6 |
| 1951 | 7.62 | 0.50 | 2.74 | 2.47 | 11.99 | 7.85 | 12.47 | 9.35 | .? | ? | ? | ? | -- |
| Total | 77.69 | 29.10 | 24.28 | 31.25 | 36.21 | 45.58 | 38.63 | 31.59 | 15.66 | 10.10 | 21.00 | 46.27 | 352.4 |
| Avg. | 8.63 | 3.23 | 2.69 | 3.47 | 4.01 | 5.51 | 4.29 | 3.51 | 1.83 | 1.26 | 2.62 | 5.78 | 44.2 |

Table 1. Rainfall at Government Station, Onotoa Atoll

(courtesy British Colonial Govt.)

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Total Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1946 | ? | ? | ? | ?. | ? | ? | 13.68 | 4.22 | 1.56 | 5.19 | 9.28 | 11.24 | --- |
| 1947 | 18.49 | 3.09 | 4.33 | 3.72 | 9.97 | 8.19 | 3.21 | 2.26 | 0.81 | 2.47 | 4.77 | 10.83 | 72.14 |
| 1948 | 21.21 | 9.35 | 18.02 | 15.97 | 8.43 | 8.99 | 6.04 | 4.69 | 1.11 | 1.28 | 5.31 | 15.09 | 115.49 |
| 1949 | 30.04 | 8.07 | 11.05 | 15.96 | 2.77 | 2.79 | 14.74 | 0.13 | 2.28 | 0.36 | 1.56 | 1.27 | 91.02 |
| 1950 | 0.52 | 0.17 | 0.15 | 0.67 | 0.49 | 0.49 | 0.59 | 3.00 | 1.20 | 1.80 | 2.72 | 3.73 | 15.35 |
| 1951 | 9.00 | 2.24 | 2.37 | 8.96 | 11.51 | 11.51 | 10.23 | ? | ? | ? | ? | ? | -- |
| Total | 79.26 | 22.92 | 35.92 | 45.28 | 29.06 | 31.97 | 48.49 | 14.30 | 6.96 | 11.10 | 23.64 | 42.16 | 294.00 |
| Avg. | 15.85 | 4.58 | 7.18 | 9.06 | 5.81 | 6.39 | 8.08 | 2.86 | 1.39 | 2.22 | 4.73 | 8.43 | 73.50 |

Table 2. Rainfall at Betio Island, Tarawa Atoll

(courtesy British Colonial Govt.)

In terms of the many characteristically "wet" atolls of the Pacific, where yearly rainfall commonly averages 100 inches or more, Onotoa is truly a "dry" atoll. This, of course, is immediately evident from its sparse ground-cover vegetation. Its climate over a period of years shows no clear division into rainy season and dry season--merely a slight tendency to be drier during September through November and less dry during December, January, and June. This, in turn, suggests only a slight correlation of relative dryness with the season of prevailing easterly trade winds (about late June through November) and of relative "wetness" with the season of more variable winds (about December through early June). Even in the Gilberts Onotoa is relatively dry as compared with an atoll like Tarawa (table 2), which averaged 73.5 inches of rainfall per year from 1947 through 1950.

Statistics for the drought year 1950 at Onotoa and Tarawa are given in tables 1 and 2. At such times the rainfall is insufficient to maintain a fresh-water head, permitting invasion of salt or brackish water through the pervious island sediments and rock foundation. The ground water in the narrower parts of the islands is soon contaminated, with resultant death of breadfruit and eventual death even of coconut trees. Taro too may be adversely affected, although it is ordinarily planted far enough inland to escape the worst effects, and at least one variety found on Onotoa survives in slightly brackish water. To judge from field observations, the only reasonably safe answer to the loss of plant products by drought is to avoid planting breadfruit, coconut, or taro on parts of islands less than 800 feet wide (or, better, 1000 feet wide) and to plant breadfruit not nearer than about 200 feet from standing salt water in any direction.

The effects of drought on ordinary water supply are judged to be less serious than on vegetation. The fluid drunk in largest volume by natives is

green coconut milk, which is self purified. Water for cooking and incidental drinking can be slightly brackish without deleterious effects, and the fresh-water lens of a permeable island area $\frac{1}{4}$ mile or more wide should survive the moderate draft of an endemic island population even during drought periods, especially if washing water is drawn from sources already gone brackish.

## PLACE NAMES

The importance that one attaches to the name of a place depends on his perspective. The Gilbertese, living in his atoll universe and dependent on the sea for a living, attaches great significance to the passes in the reef through which he can safely sail his outrigger canoe, to the reefs on which he might wreck it, and to the parcels of ground on which he and his neighbors live and over which they quarrel. He is not interested in names for a whole island or islet, except as it happens that the smaller islets are commonly single parcels of real estate. He does not go to the north or south end of some named island or islet, he goes to some particular named property or to the home of some fellow Onotoan at the village of Temao (tĕ-mä-o) or Tekawa (te-kä-wå).

On figure 2 only a few of the more important place names are given. The names of the seven villages are capitalized. Several islets that coincide with property divisions are indicated by the names of those property divisions in lower case lettering. The few reef names used are indicated by the Gilbertese word for reef, rakai (rá-kī); except for Aon te Baba (än-tĕ-bä-bå) and Aon te Rabata (rå-bä-tå), to the north and south respectively of the main passage. Aon means on, and te is the definite article, the two together being used in a sort of vernacular sense in combination with the designating name, as we speak of "Smith's place" or "at Joe Webbs" in English. With continued usage such designations take on a sort of formality, and even come to be run together as a single word (like Pittsburg, Beekmantown, Yorkshire, and Aonteuma (än-tĕ-ŭ-ma)).

There is nothing to call the two main islands of Onotoa except the north island and the south island unless names are concocted, and nothing would be

gained by this - the Gilbertese would be bewildered, and Onotoa is already a small enough named subdivision in world geography. The headquarters of the Colonial administrative office on Onotoa is at a place called Buraitan (Bur-i-tån). However, as frequent reference is made to this place and our campsite at its south edge, and as the land areas on the larger islands are not named, it seems easier for the reader to call this place Government Station. For the same reason it seems better that the anchorage be called just that, rather than Komotu (literally anchorage, in Gilbertese).

The authenticity of the names used, as well as the dozens of others not shown on the preliminary map, was checked in the field at every opportunity and finally reviewed on the last day of our sojourn by a group of six "old men" or Unimani (community elders respected for their knowledge) representing five of the seven villages. Because of the close village life and regular habits and travels of the people a man from one part of Onotoa may be quite unfamiliar with names for natural features of other parts of the atoll (the reefs and passes especially), but the concordant judgement of the committee of six would certainly be accepted as final by most Onotoans.

Pronunciation is another problem. To reduce it to its simplest immediately pertinent and practical terms keep in mind that the sound indicated by b is almost that of the letter p, the combination ma sounds like mwa with an almost imperceptible w, the terminal ti is pronounced like an s, and other terminal i's are silent. Rules for syllabification and emphasis are more complicated, but pronunciation is indicated for important words upon their first use in this report.

## GENERAL FEATURES OF THE LAGOON

Reference to figure 2 will show the general shape of the Onotoa lagoon bottom as contoured from 21 echo sounding traverses, a few spot soundings, and submarine details visible on air photographs. This chart may not be relied upon in detail for navigation, however. In general, the underwater contour lines refer only to the general depth of bottom between patch reefs. Although a few large patch reefs are individually contoured, no indication is given of the positions of the numerous small reefs that reach to or near the surface over a large part of the lagoon.

Unless one has learned some particular channel or is completely familiar with the lagoon, he should not attempt to negotiate its waters in any kind of boat (including canoes) without keeping a very sharp lookout for reefs and shoals, and he should avoid travel on the lagoon at night. For ordinary ships' boats the only reasonably clear shore approaches are within the segment defined by lines of fathometer traverses A and 8 to the jetty at Government Station and about along or a little south of the line of traverse G to the Maneaba (Mwȧ-ē-ȧ́-bȧ) at Aiaki (ī́-ăk). A course along traverse G would need to evade linear patch reefs between 4000 and 5000 feet offshore, and there is no anchorage for ships off the outer reef here. There are no navigation lights or buoys anywhere, and the only good sighting points are the ends of islands, the white stone monument on Aonteuma, and the churches and large community meeting houses, or Maneabas, shown on figure 2.

The only suitable anchorage for larger vessels at Onotoa is on the leeward shelf outside the gap in the outer reef opposite Government Station. This is a well-protected anchorage except at the rare times of westerly winds. It has a good holding bottom and adequate swinging room. It is reported

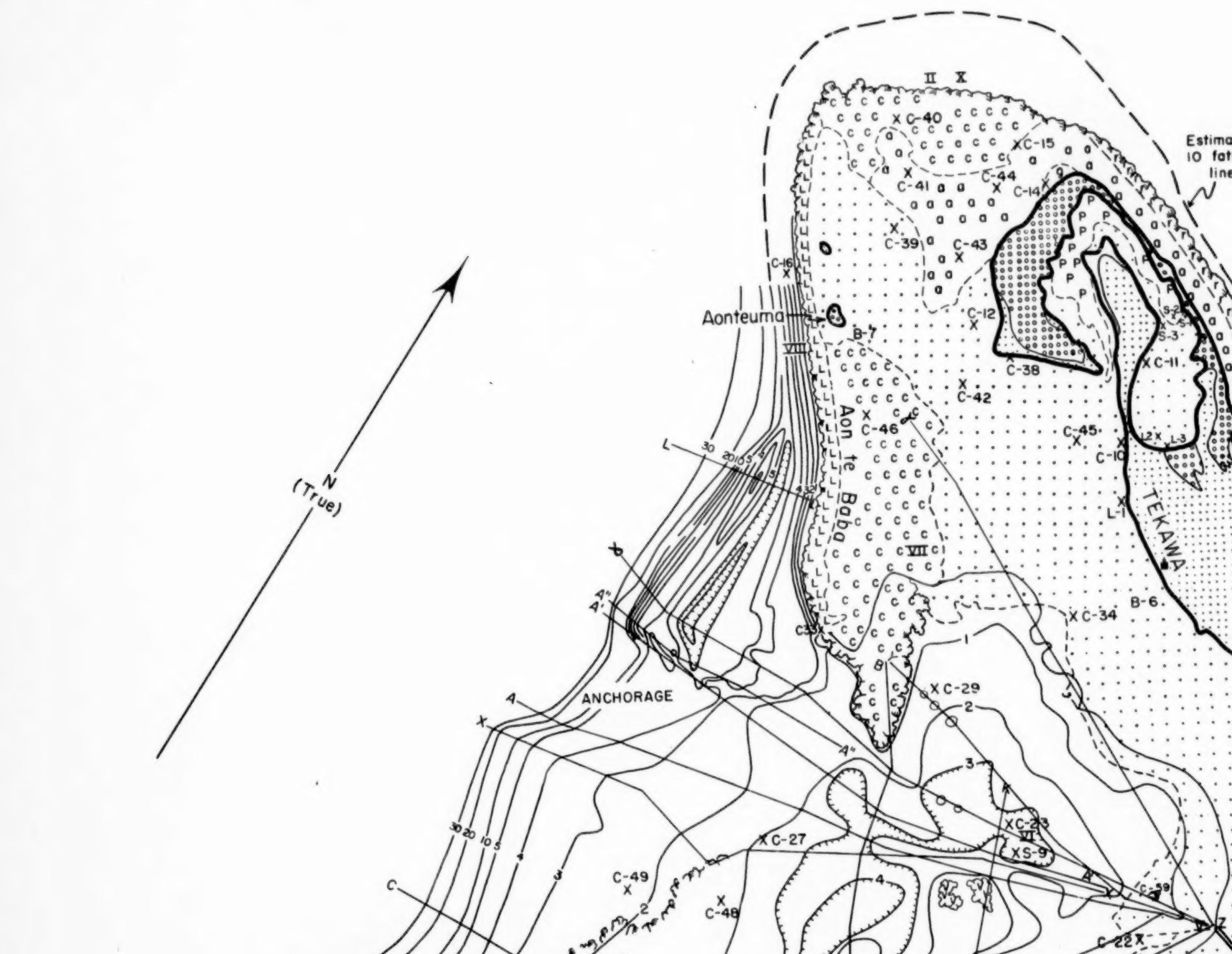
(U. S. Hydrographic Office, 1940) that small ships may anchor near "Taburari" (Tȧb-ü-ȧr-ôr-ī) at the south end of the island. However, the only possible anchorage at this place is a very narrow shelf right against the reef and generally swept by a rolling swell from the south--an undesirable anchorage except at times of dead calm. To my knowledge, no vessel of any size has ever entered the Onotoa lagoon. It would be possible, however, by careful manipulation, to work a vessel of less than 9-foot draft into the lagoon and anchor it there, and it might be worth doing if one were to be there beyond a few days. It would also be possible to clear channel and anchorage in the lagoon for regular use by vessels up to 9-foot draft.

The intended reference datum for the depth contours in figure 2 is mean low low tide. This datum can be only roughly approximated, as the U. S. Coast and Geodetic Survey "Tide Tables" for 1951 give no correction factors for Onotoa tides. They do give records for several other Gilbert atolls, and I have arbitrarily assumed the same corrections as for Nonouti (nō-nüch), with Kwajalein as reference point. This gives 6.2 feet as the spring range of tide and 4.4 feet as the mean range of tide. No effort was made to make a precise check on these data, but the assumed ranges and times seemed about right in the field, with considerable local lag in enclosed tide flats and tidal inlets.

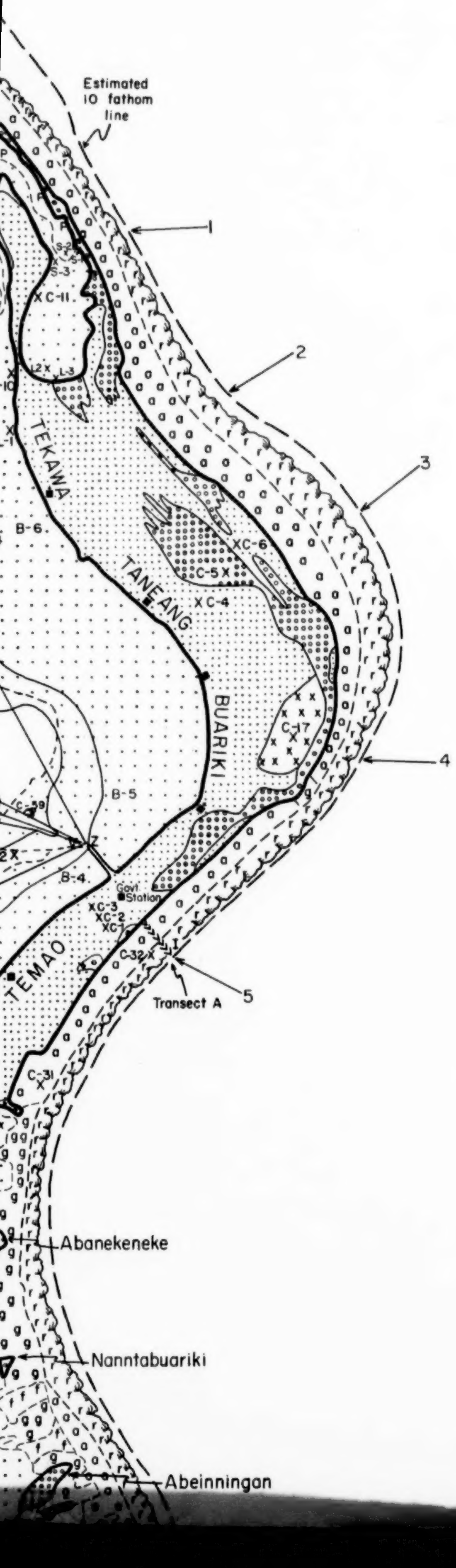
Depth traverses were made with Navy Model NK-7 portable echo sounding equipment, which consists of a magnetostrictively actuated transmitter-receiver unit in an outboard wooden fish and a recorder unit that produces a continuous graphic record on a strip of sensitized chart paper. This fathometer was carried in a 20-foot flat-bottomed dinghy driven by a 7-horsepower outboard motor. It was operated by two parallel-connected 6-volt automobile batteries which proved of inadequate capacity to maintain the sensitivity required to operate at depths below 200 feet for more than very short periods.

A clear record was produced, however, from depths of 200 feet on the outer reef slope into very shoal waters, and, after approximate correction for tide conditions and depth below surface of the transmitter-receiver fish, this record was accepted as the basis for contouring the bottom of the lagoon and upper reef slopes.

Figure 2 shows that the lagoon is very shallow, its maximum depth of 8 fathoms being based on two hand-lead soundings at and near locality C-55. The general bottom topography (excluding the numerous small patch reefs) consists of three shallow basins. The south basin is the largest and deepest, generally deeper than 6 fathoms in its central part and attaining a maximum of 8 fathoms. The central and north basins connect and might be thought of as a single long narrow basin generally exceeding 3 fathoms in depth and attenuated in the middle. The central basin proper exceeds 4 fathoms over a fairly large area and 5 fathoms locally. The north basin has only a small area that is deeper than 4 fathoms. All three basins are separated from one another and from the outer deeps by shelves of 2- to 3-fathom depth. In the passes through the outer reef the depth nowhere much exceeds 2 fathoms. Between the many patch reefs the lagoon bottom is everywhere floored with calcium carbonate sand, silt, or gravel.



N (True)
Aonteuma
Aon te Baba
TEKAWA
ANCHORAGE
Aon te Rabata
Rakai Teeka
Rakai Ati
TEMAO
C-40
C-15
C-44
C-41
C-14
C-39
C-43
C-16
B-7
C-12
C-38
C-42
C-46
C-45
C-10
C-11
L-1
B-6
C-34
C-29
C-23
S-9
C-27
C-49
C-48
C-22
B-4
B-8
B-1
B-2
B-3
C-31
C-50
C-37
C-24
C-36




## EXPLANATION

Limesand

Limegravel

Natural depression

Green alga zone of windward reef flat

Red alga zone of windward reef flat

Leeward reef flat
(Green algae lagoonward, red algae and sturdily branching forms of the corals *Acropora* and *Pocillopora* seaward)

Dead reef surface, generally with gravel veneer

Foraminiferal flats
(Living *Calcarina* and *Marginopora* matted in soft algae)

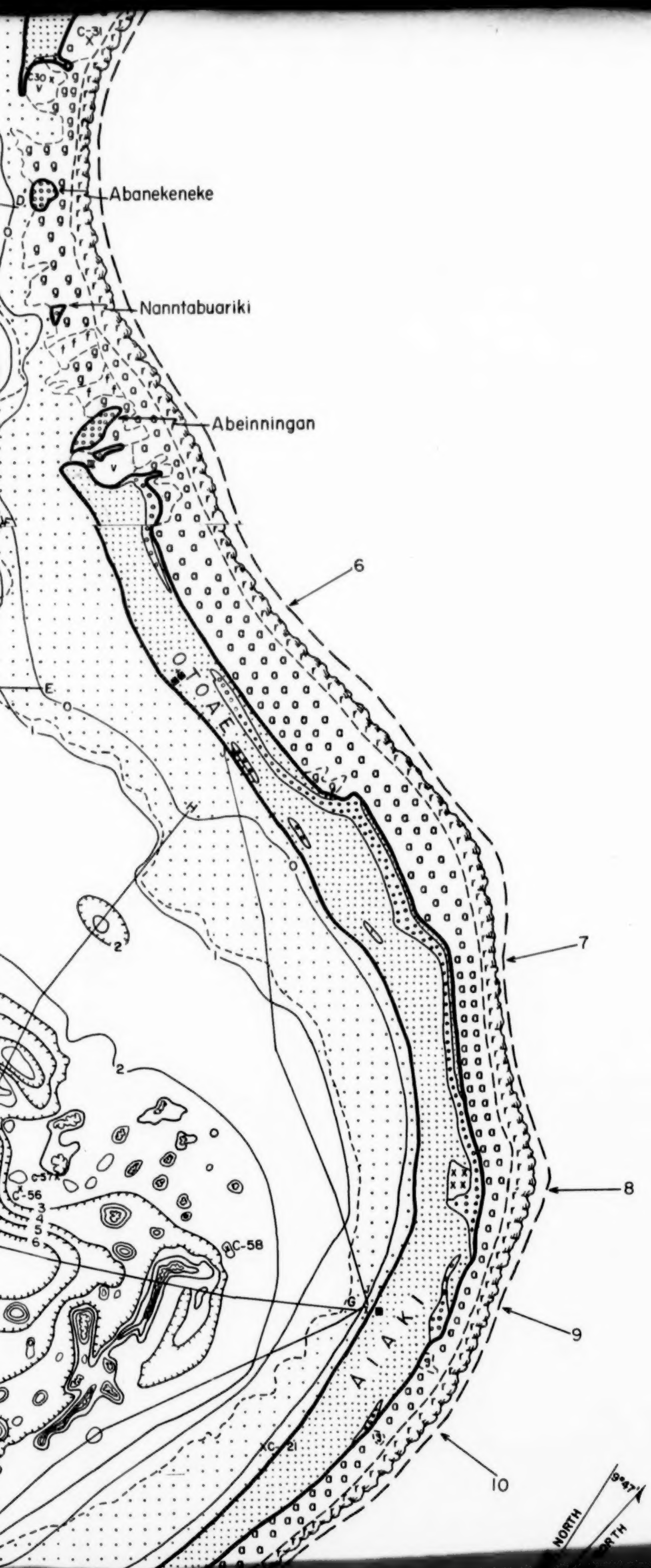
Reef area of abundant living coral of few types

Reef area of scattered living coral of many types.
(Varied coral types scattered on bottom of dead coral-algal rock that is veneered with limesand and limegravel)

Tidal inlet

Tide flats and shoal water areas of sand, gravel, dead coral-algal rock or any combination of these
(Locally with patches of turtle grass *Thalassia*, green algal growth and sparse living coral)


Teeka
D
C-37
Rakai
Ati
C-24
C-36
E
XC-28
C-51
XC-25
Rakai
ni Maike
C-52
G
XC-55
C-53
X C-35
IV
MB
XC-54
F'
F
TABUARORAE
B-2
C-30
C-31
C-56
C-57




Reef area of scattered living coral of many types (Varied coral types scattered on bottom of dead coral-algal rock that is veneered with limesand and limegravel)

Tidal inlet

Tide flats and shoal water areas of sand, gravel, dead coral-algal rock or any combination of these (Locally with patches of turtle grass *Thalassia*, green algal growth and sparse living coral)

High tide line

Margin of wave-breaking reef

Front of submerged reef area

Boundaries between intertidal and related shoal units

Number and guide line to geology-soils profiles

F——F
Designation and course of fathometer traverse

Approximate location and depth in fathoms below mean low low tide of generalized underwater contour line. (Hatchures point toward closed depression. Surface indicated is generalized bottom surface - above this rise numerous patch reefs, some awash at low tide)

X C-28, X S-7, X L-2

Selected collecting locality of P. E. Cloud Jr. S sediments, L lithology

B-1 to B-8

Collecting localities of A. H. Banner

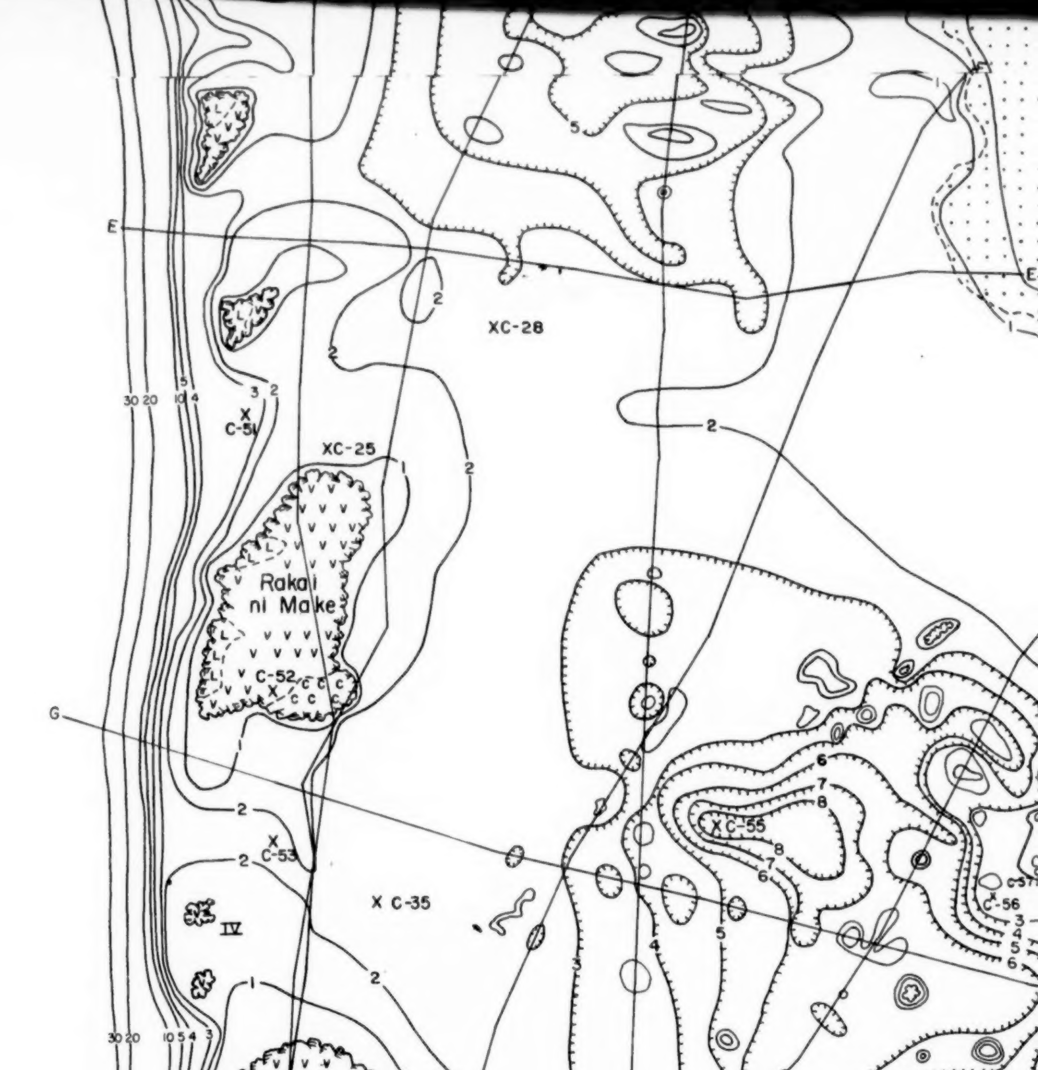
I to X

Fish collecting localities of John Randall

>>>>>

Transect A

Maneaba




Base compiled from aerial photographs, using ships bearings and taped traverses for control. Adjustment by inspection.

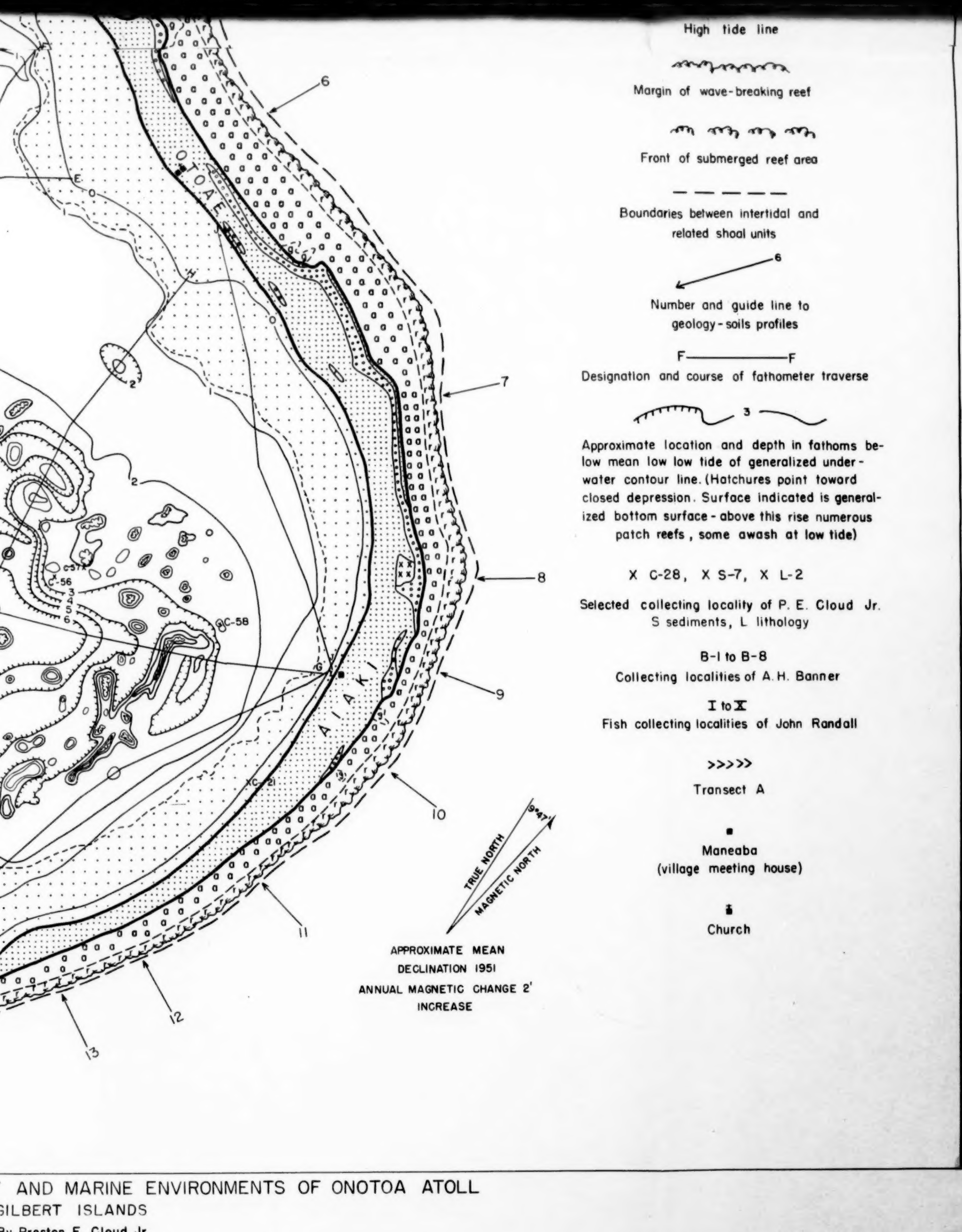
FIGURE 2. GENERALIZED GEOLOGY AND MA

GILBERT IS

By Preston E.

0 1/2 1

0 50




AND MARINE ENVIRONMENTS OF ONOTOA ATOLL

GILBERT ISLANDS

By Preston E. Cloud Jr.

1 2 Miles

5000 10,000 Feet

## PRINCIPAL ECOLOGIC AND SEDIMENTARY SUBDIVISIONS

Systematic studies of the plants and animals, and chemical and mechanical analyses of the sediments and rocks of Onotoa are still in progress. Until these are completed it seems preferable here merely to mention some of the more general or interesting facts and inferences about the principal habitats and deposits of this atoll. As a possible aid to those engaged in comparative studies of atolls, brief descriptions of ecologic and sedimentary units as recognized in the field are given in Appendix B.

### Islands

The land area of Onotoa is given by Leonard Mason (In Freeman et al., 1951, p. 274) as 5.2 square miles and the lagoon area as 21 square miles. The land surface is mostly unconsolidated sand and gravel (fig. 2). Solid rock is rare. The sand, gravel, and rock are entirely of calcium carbonate (except for the generally small magnesium content of some algae and shells), a little humus, man-carried debris, and minor amounts of siliceous pumice that has been washed up from distant volcanic eruptions. As they are thus all limesands, limegravels, and limestones, the prefix "lime" (used by geologists to signify $CaCO_3$) should be understood where not actually used in the following pages.

If Onotoa were part of an extensive land area, probably no geologist would make finer distinction of its sediments than that between sand and gravel. Because its land area is small, however, and because details of sediment distribution may be helpful in understanding processes, effort was made to distinguish, and in a general way to map as many different kinds of sediments as could be recognized. For soil classification and vegetation relationships it seems also likely that only a few main types of soils should be recognized:

(1) loose limesands with a well-marked humus layer; (2) loose limesands without a humus layer (younger dune sands); (3) tight-packed, low-lying, generally damp and brackish limesilts and very fine-grained limesands; (4) indurated, phosphatized (?) limesands (old dunes); (5) coarse gravels; and (6) pebble gravels. The properties of the finer pebble gravels at places approach those of the loose limesands, and impinging units ordinarily show gradational relationships.

Soil profiles were run at five localities on loose limesands, at a sixth locality on pebble gravels, and at a seventh on limesilts; and depth of humus was observed at many localities. Tests with a standard Truogg soil testing kit gave a pH of 8.1 for the surface layer of all profiles except that on the damp limesilt, and this had a pH of 8.0. There seemed a slight tendency for pH to increase a little with depth, to as high as 8.3 well below the thin soil layer in fresh parent limesands, but no reading above pH 8.3 was made at any depth. It is difficult, however, to be sure of Truogg index colors as closely as the foregoing suggests, and the difference between 8.0 and 8.3 might be imaginary. Maximum recorded thickness of a well-defined humus layer was 10 inches, but 5 to 8 inches was commoner. At most places in the limesands a zone of slight organic staining extended another 10 to 19 inches beyond the humus layer. Roots were common to depths of 2 to 3 feet and have been encountered at depths as great as 4 feet below the ground surface in freshly dug pits.

As will be brought out by the botanist's report, vegetation zones show a general relation to soil types, especially in certain elements of the ground cover. However, an overriding effect is exercised on vegetative patterns by exposure to wind and salt spray, by the nature of the ground water (related to width of land, distance from sea or lagoon, and height of land), and by artificial factors.

## Intertidal environments except reefs

Under intertidal environments are included beach areas, flats that are mainly intertidal, and bars. Reefs, and areas that range from intertidal to lagoonal are considered elsewhere.

The biota of the beaches, tide flats, and bars is generally distinctive. Sand beaches support little in the way of a megafauna--only ghost crabs (Ocypode sp.) and, at some localities on the lagoon side (e.g. C-38), closely packed layers of a small edible pelecypod (Atactodea sp.) an inch or two below the surface of the sand in the mid-tide zone. On rocky beaches, on both seaward and lagoonward sides, a neritid snail close to Nerita plicata Linné is commonly very abundant, and a high-spired littorinid probably referable to a species of Melaraphe is locally abundant. On rocky and gravelly seaward beaches the common tropical Pacific scavenging crab Grapsus grapsus (Linné) is abundant. Sand bars are very nearly devoid of a megafauna, but burrowing sipunculids may be found. The intertidal flats display a wide biotal variation that will not be discussed here, but some elements of which are noted in Appendix B.

## Outer reef

An atoll consists of a ring-shaped outer reef and a central depression or lagoon. In plan view the outer reef is generally irregular in outline and is interrupted and divided into segments by passes. In modern seas islands are commonly located on the reef platform. The lagoon ordinarily contains small patch reefs of a variety of shapes, and, in some places, submarine benches lie beyond the crest of the outer reef. By definition the lagoon of an atoll can contain no pre-existing land, but this would not exclude islands that might be founded on patch reefs. The ring-shaped outer

reef is the essential and most conspicuous feature of an atoll and the subject of the immediate discussion. Patch reefs will be considered under a following section on environments of the lagoon and leeward shelf.

A conspicuous feature of the outer reef, especially in the Gilbert Islands, is the difference between windward and leeward sides. With the exception of Butaritari (or Makin, Mŭ́gĭn) and Marakei, the atolls of the Gilberts show continuous wave-breaking reef and almost continuous land on their windward (east) sides. Their leeward (west) sides are characterized by irregular outer reefs and few or no islands. All passes into their central lagoons are to leeward. The windward reef flat of Onotoa (also observed parts of Tarawa and Butaritari) is generally exposed at low tide and is veneered with algae. The leeward reefs are commonly submerged for a few feet over most of their area, even at low tide. At many places they show relatively vigorous coral growth--locally even continuous veneers of closely packed living coral. A feature of some Gilbert Island atolls, established for Onotoa but also noted at observed parts of Tarawa and Butaritari, is that at least the upper part of the reef frame was built primarily by the blue coral Heliopora, an alcyonarian, and not a typical stony coral or scleractinian (see also Finckh, 1904, p. 136). That this may be commonly or even generally true for the Gilbert and Ellice Island groups is further suggested by the observations of David and Sweet (1904, pp. 66-70) at Funafuti. Here Heliopora was the frame builder to a depth of 40 feet below high tide in the main bore and occurred in the cores to depths of at least 100 feet.

The ecologic niches of the outer reef may be grouped into those of the reef slope, the reef front (with coralline ridge and surge channels), and the reef flat, the greatest variation being in the reef flat environment.

The relationships of the most persistent recognizable units are shown on figure 3 (profiles 2 and 5)--these being the green alga zone, the red alga zone (including back ridge trough), the coralline ridge, and the benched reef slope of the windward reef.

## Intertidal to lagoonal environments

At Onotoa, flats and shoals with extensive growth of the marine grass Thalassia, as well as generally barren rocky flats and shoals, overlap widely from the intertidal to the lagoonal environment and are thus separated from both. Coral veneered rocky shoal bottom is strictly of the shoal lagoon, but it is so closely related to adjacent sparsely coralliferous rocky flats and shoals that it is included with the intertidal to lagoonal environments as a matter of convenience. It is also convenient to include under this heading certain enclosed inlets which, although permanently inundated and similar to the lagoonal units, are separated from the lagoon proper by extensive tide flats.

## Environments of the lagoon and leeward shelf

The area here referred to as the leeward shelf is that which extends north and south from the anchorage, beyond the main passage between lagoon and anchorage (see figure 2). Ecologic zones and deposits of the lagoon and leeward shelf may be roughly delimited according to variations in areal importance of patch reefs or veneering coral growth as contrasted with limesand bottom. They may also be further broken down on the basis of differences in the dominating reef-building organisms. The probable nature of the formerly luxuriant growth of Heliopora is well illustrated in the present lagoon by areas of Heliopora patch reefs and limesand.

The effect of certain fish in the production of lagoonal sediments is of special interest. Darwin observed that fish browsed on coral, and Couthouy (1844, p. 97) was aware that lagoonal sediments might "partly arise from the excretions of certain fishes." Safford (1905, p. 90) and Newell et al. (1951, p. 13) also observed fish nibbling on coral, but Finckh (1904, p. 141) states that "although a large number of kinds (of fishes) were watched in the neighborhood of coral, in no instance were they seen to browse on it." There is no doubt, however, that fish do browse on coral, and they probably are important contributors to the sediments around reefs.

The scarids (parrot fish), with their parrot-like jaws, and the acanthurids (surgeon fish), chaetodontids (butterfly fish), and pomacentrids (damsel fish), with their fused comb-like teeth, appear to be primarily browsers on soft algae. Significant to sedimentation is the fact that, in course of feeding, fish from these families scrape off thin layers of the dead calcium carbonate substrate. This was verified by examination of their gut contents. These fish are so numerous and active that they probably produce a fairly constant rain of this fine $CaCO_3$ debris, and, indeed, schools of scarids commonly defecate great clouds of it when startled. In course of time this must represent a considerable contribution to the lagoon sediments.

A coarser sedimentary product is added by the balistids (trigger fish) and monocanthids (file fish), which are armed with a massive dentition of grouped biting teeth, and by the tetraodontids (puffers), which have parrot-like jaws similar to those of the scarids. Their stomachs contain the fresh tip ends of branching corals up to 5 by 10 millimeters and some have yielded chunks of crustacean tests and spines and plates of echinoids, as well as

algae. They have been observed actually to bite off the tips of coral branches, and the fresh pieces of coral in their guts are free of fleshy parts. Doubtless these fish provide a significant part of the coarse fraction of lagoonal sediments.

It is believed that fish are more important in the production and trituration of lagoon sediments than either echinoids or holothurians, the two groups that are most frequently cited as organic sediment producers. In making this argument I mean, of course, to emphasize a commonly neglected or unrecognized factor in lagoonal sedimentation, not to deny the significance of other factors. The calcareous joints of the green alga Halimeda locally bulk large or even dominate in lagoonal sediments (e.g., David and Sweet, 1904, p. 65), and Foraminifera and coralline algae contribute significantly to these sediments through their dead shells and joints. The spicules of gorgonians and other alcyonarians (Carey, 1918, 1931) and the tests of ostracodes are likewise contributing elements. Detrital products strictly due to abrasive wave action and derived from both outer reef and patch reefs also contribute to the lagoonal sediments, but probably do not bulk as large in their overall mass as might be supposed.

The foregoing and other matters related to the ecologic zones and deposits of the lagoon and leeward shelf will be considered more fully and critically when laboratory studies are completed. For the present it must suffice to note that the obvious variations in the shallow lagoonal environment comprise differences in density of concentration of patch reefs. Patch reefs are very abundant and locally almost continuous toward the leeward reefs and passes and gradually decrease in number toward the island mantled windward reef platforms. Linear to irregular areas of bare limesand alter this gradational sequence only locally.

## ORIGIN OF BEACHROCK

Beachrock results from lithification of beach debris in the intertidal zone owing to factors not fully understood but apparently peculiar to saline waters that are saturated with calcium carbonate. It is common on tropical sea beaches. It characteristically has the slope and mechanical composition of the constituent beach materials, whatever these may be. Beachrock is mentioned in most reports that discuss the shore-zone geology of tropical islands and has been discussed at length in several papers. A recent summary is by Emery (in Pac. Sci. Board, 1951, p. 34). It is evident that cementation of beach sands to make beachrock results from interstitial precipitation of calcium carbonate in the intertidal zone, but the mechanism of such precipitation is not agreed upon. The ensuing discussion will emphasize the importance of algae in beachrock formation.

Onotoa is an almost ideal laboratory for the study of beachrock, for hard beachrock and bonded limesand occur there over large areas. Bonded limesand, considered to represent incipient beachrock, was found on lagoon beaches, in tide pools and spray pools, and as broad carpets in tide flat areas. It was not found anywhere on the seaward beach at Onotoa. On some tide flats the penetration of fairly solid beachrock by numerous burrows of a small red-clawed fiddler crab (Uca sp.) strongly suggests that the burrows were dug prior to induration of the rock. Everywhere that bonded limesand was found on Onotoa it was observed to be encrusted with living blue-green algae of several genera and species (see descriptions in appendix B). These algae apparently bind the beach and tide flat sands at the surface and, through their biologic activities, may cause or accelerate interstitial precipitation of calcium carbonate beneath. Some samples of the supposed incipient beachrock show successive alga-capped layers or laminae, and it

looks very much as though the algae play the important function of holding the sands in place until they can be indurated.

I am satisfied that the formation of beachrock in protected localities is brought about by, or greatly accelerated by, the activities of blue-green algae and hope to document this fact more fully in a later report. It is difficult, however, to see how ordinary blue-green algae could have a significant effect on the bonding of conglomerate beachrock on an exposed seaward beach. Perhaps the answer is that beachrock does not form on exposed beaches except in protected places or during times when wave action is very weak. A sample of firmly bonded gravelly sand containing numerous brass cartridge shells was collected on a seaward beach at Tarawa, but this had formed in a pocket behind ledges of older beachrock and was encrusted and ramified with soft algae. If any given locality were free from strong wave action only long enough for algal bonding of beach detritus to get a good start, cementation might continue when the locality again was exposed to more vigorous wave attack.

## HYDROLOGY

Hydrologic observations made were limited by time, facilities, and staff. Several samples of ground water and one sample of sea water were taken for chemical analysis (not completed); some observations of movement of dyed water across and beyond the windward reef were made; and diurnal variation of pH, temperature, and chloride ion concentration was observed at selected localities. In addition, some determinations were made of total hardness, calcium hardness, and magnesium hardness, all "as $CaCO_3$," and of calcium and magnesium ion concentrations. Chloride was determined by titrating with silver nitrate and potassium chromate, and hardness factors were determined with stock hardness indicators and sodium hydroxide as described by D. L. Cox (Pac. Sci. Bd., 1951, pp. 22-26). Observations of pH were started with a Gamma electric meter using glass and calomel electrodes, but, owing to battery failure, it was necessary to complete this study with a Japanese-made (Mitamura) set of colorimetric indicators. Colorimetric indicators, unfortunately, are neither as reliable nor as finely calibrated as the electric meter.

In the ensuing discussion the term "chlorinity" refers to the concentration of the chloride ion ($Cl^-$) in parts per million of solution.

### Ground water

Ground water in the permeable medium of an atoll island occurs as a lens of fresh water floating in hydrostatic balance on salt water below. As fresh and salt water are miscible, a zone of mixing occurs at the contact of the fresh-water lens with the salt water below. Various irregularities in the shape and integrity of the lens may result from openings, passageways, or

variations in permeability of the island foundation that accelerate or retard mixing. A ground water lens of this sort is called the Ghyben-Herzberg lens, after two of its early propounders, and it is succinctly discussed by Wentworth (1947).

The source of fresh water in the lens is rain. Given adequate rain and unvarying permeability, the thickness of the lens depends on its areal dimensions and the amount of loss through evaporation or artificial draft. As a result of the difference in density between about 1.000 for fresh water and about 1.025 for sea water, the thickness of the balanced lens, assuming no mixing, should be 40 times the height to which the balanced fresh water extends above sea level. In small islands or very narrow parts of long ones the fresh-water lens will be relatively thin and brackish. In large islands of medium and consistent permeability, assuming adequate rain, the lens will be thick and the water potable. In time of drought this fresh water, in parts of islands wide enough to have a reasonably thick lens, would be lost only slowly by diffusion, mixing, and outflow. Heavy draft without recharge, however, leads to salt-water invasion.

Ample demonstration that the ground water of Onotoa comprises a lens of the Ghyben-Herzberg type is provided by observed diurnal variations of the level of ground water at site C-2 (center of island, shower well at camp). This level fluctuated through $16\frac{1}{2}$ inches with a tide range at the time of about 4.3 to 5.5 feet, and its high and low stands followed the high and low tides with a lag of 2 to $3\frac{1}{4}$ hours. Obviously, the fresh water is affected by the tides and must be floating on interstitial sea water in the permeable sediments and rocks beneath.

Eight ground water samples were studied from an area about $\frac{1}{4}$ mile square and centering on the Government Station and our campsite (figs. 2, 3). This

area was selected for study partly as a matter of convenience and partly because the island at this place approaches the probable minimum width (1000 to 1400 feet) required to maintain a fresh-water lens continuously through drought periods of recorded duration.

Results of field tests on this ground water are given in table 3. Samples 1 to 5 were from wells dug and maintained prior to the arrival of the American field party. Sites C-1, C-2, and C-3 (fig. 3) were dug mainly to obtain ground water samples and geologic sections at regular intervals across the island. Sites 1, 2, 3, 5, and C-2 were about at the center of the island, whereas sites 4 and C-3 were halfway from center to lagoon beach, and C-1 was halfway from center to seaward beach. Of the five wells tested, the two--1 and 2--that showed lowest chloride concentrations and total hardness were at the center of the island, but one well toward the lagoon beach (4) provided potable water. Well 3, relatively high in chloride content, total hardness, and magnesium, and not good for drinking was also at the center of the island and only 225 feet south of well 2, a good well. The data of table 3, in combination with taste tests of other wells, indicate that a well toward the center of parts of the larger islands that are wider than about 1000 feet has a good chance of producing a fairly continuous supply of potable ground water under the normal draft of the native population. Wells in narrower land or near the beach are apt to be brackish. According to the principles of hydrostatic balance in the Ghyben-Herzberg lens, as the land is wider, the lens is thicker, and the chances of a sustained supply of potable water are better.

Irregularities in fresh-salt boundary relationships in the lens due to openings in the reef-rock foundation are to be expected, and the relatively

[illegible]

[illegible]

[illegible]

[illegible]

| Well or site | pH Gamma meter | pH phenol red dye | pH thymol blue paper | Chloride (ppm) | Total hardness as $CaCO_3$ (ppm) | $Ca^{++}$ (ppm) | $Mg^{++}$ (ppm) | Temp. °C |
|---|---|---|---|---|---|---|---|---|
| 1 | 7.66 | — | 7.5 | 262 | 418 | 98 | 42 | 29 |
| 2 | 7.98 | — | — | 264 | 429 | 70 | 62 | 29 |
| 3 | 7.40 | — | 7.7 | 989 | 693 | 93 | 112 | 28 |
| 4 | — | 7.7 | — | 633 | 532 | 75 | 84 | 26 |
| 5 | — | 7.7 | — | 640 | 548 | 88 | 80 | 26 |
| C-1 | 7.48 | — | — | — | — | — | — | 23 |
| C-2 | — | 7.5 | — | — | — | — | — | 23 |
| C-3 | — | — | 7.7 | — | — | — | — | — |

Table 3. Properties of ground water on Onotoa

(Note that all pH readings were made during daylight hours,

pH of wells with algae should fall at night)

high chloride and magnesium content of well 3 is possibly due to such an opening or passage. It is possible to predict the location of such openings only by methods that are prohibitively expensive with reference to the ease and cheapness of digging a shallow well. The practical way of meeting the problem of ground water supply in the Gilberts is to locate wells intended to supply drinking and cooking water at or toward the middle of islands more than 1000 feet wide and at least several thousand feet long. Some wells so located will encounter brackish water in any event, but they should be proportionately few.

### Shallow sea and tide pools

Observations were made on diurnal variation of pH and temperature of water from a high tide pool and a spray pool on the windward sea beach, from a tide pool on the windward reef flat, from flow over the reef flat, from immediately offshore in the shallow lagoon, and from a spray pool with bonded limesand on the lagoon beach. The last mentioned, though a spray pool at neap tides, is a tide pool at times of spring tide. All sites observed were adjacent to the field camp south of the Government Station on the northern main island. In addition to pH and temperature, the concentration of calcium, magnesium, and chloride in parts per million was determined.

The beach zone pools at Onotoa mostly have flat bottoms, a large population of fixed algae, and a few snails (<u>Nerita</u>) and blennies. The tide pools of the inner reef flat have smooth, shallow, rounded bottoms, commonly elongated normal to the shore and with algae growing between rather than in them. The beach zone pools are considered primarily attributable to solution. The reef flat pools are probably in part abrasion features. Emery (1946) gives results of similar but more complete studies of tide pools at La Jolla, California, and provides references to previous publications on the subject.

The results of the observations at Onotoa are shown graphically in figures 4 to 8, and critical variations in hydrogen ion concentration are summarized in table 4. From these data it is clear that, excluding extraneous factors such as affected the high seaward tide pool of figure 7, temperature, chlorinity, and pH all show the same general pattern of diurnal variation. This pattern is a recumbent sigmoidal curve, rising to a peak during the day and falling to a low at night. Moreover, samples tested for $Ca^{++}$ and $Mg^{++}$ show that these properties vary directly with chlorinity.

The batteries of the electric pH meter gave out toward the end of the first set of 24-hour readings, but sealed water samples had been taken for all hours read and these samples were immediately checked with a Japanese-made (Mitamura) set of fluid and paper colorimetric indicators. These indicators showed consistent results following a diurnal variation curve similar to that of the electric meter but generally reading 0.3 to 0.5 unit higher and tending to flatten the curve slightly toward the peak. This check makes credible the general range of readings subsequently made with the colorimetric indicators, but also suggests that the colorimetric curve should be scaled somewhat lower than it actually reads.

Data from the shallow lagoon (fig. 4) and water in flow over the windward reef flat (fig. 5) may be taken as an approximate measure of the limits of normal variation in the very shallow marine waters of Onotoa. These show a range in chlorinity of 18,080 ppm $Cl^-$ just before daybreak to 20,680 ppm $Cl^-$ during the day. The pH (meter measured) ranges from 7.63 at midnight or early morning hours to 8.80 in midafternoon, and temperature ranges from 23.5° C just before daybreak to 34° C at midday. The lowest pH recorded electrically was 7.63 for water in flow from beyond the outer reef over the reef flat at midnight, and the highest was 9.05 for water in a then stagnant reef flat tide pool at midtide and midafternoon. This range is close to the range found

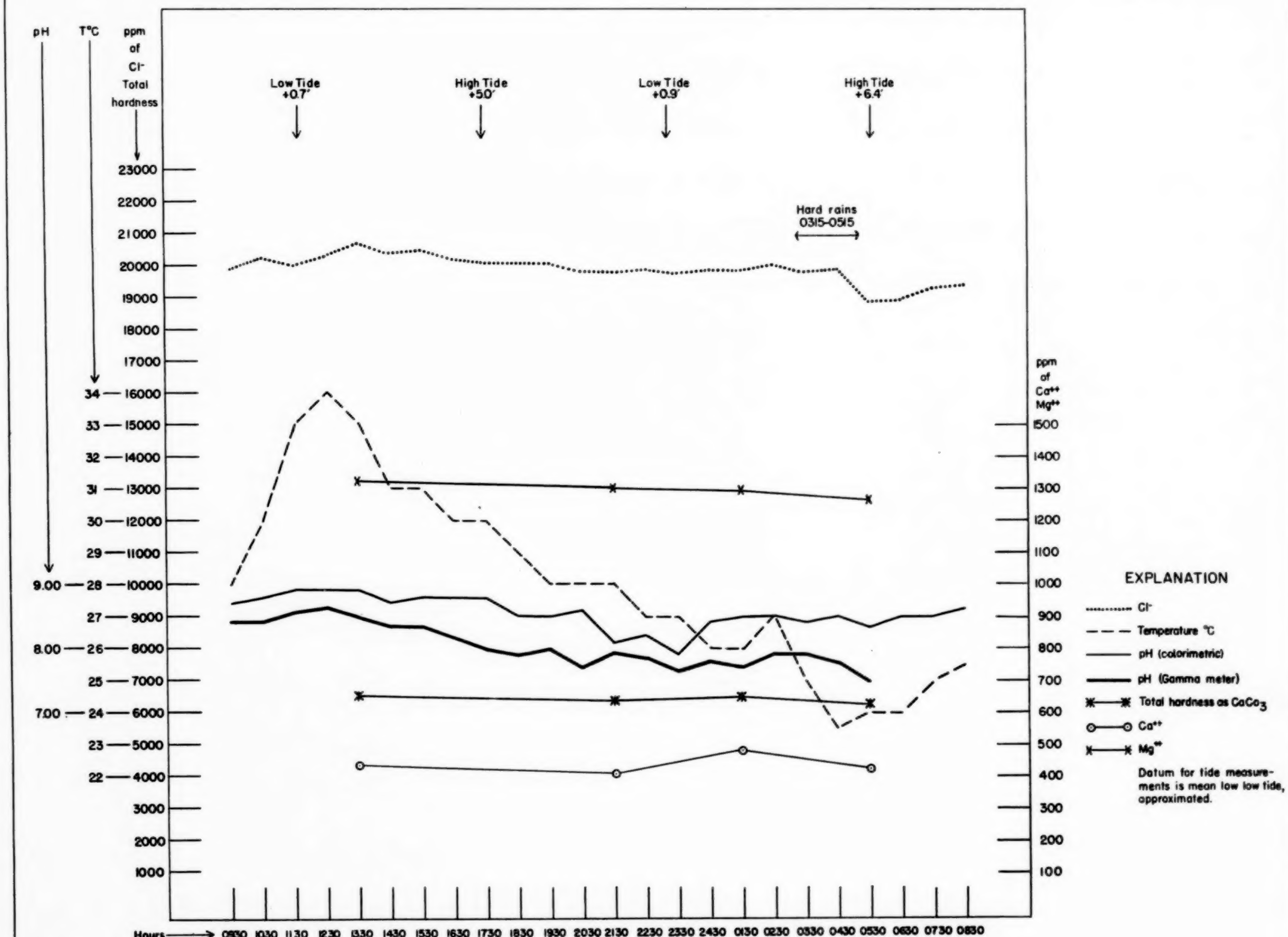



FIGURE 4. PROPERTIES OF SHALLOW WATER IN NEAR SHORE LAGOON (JULY 6-7, 1951)

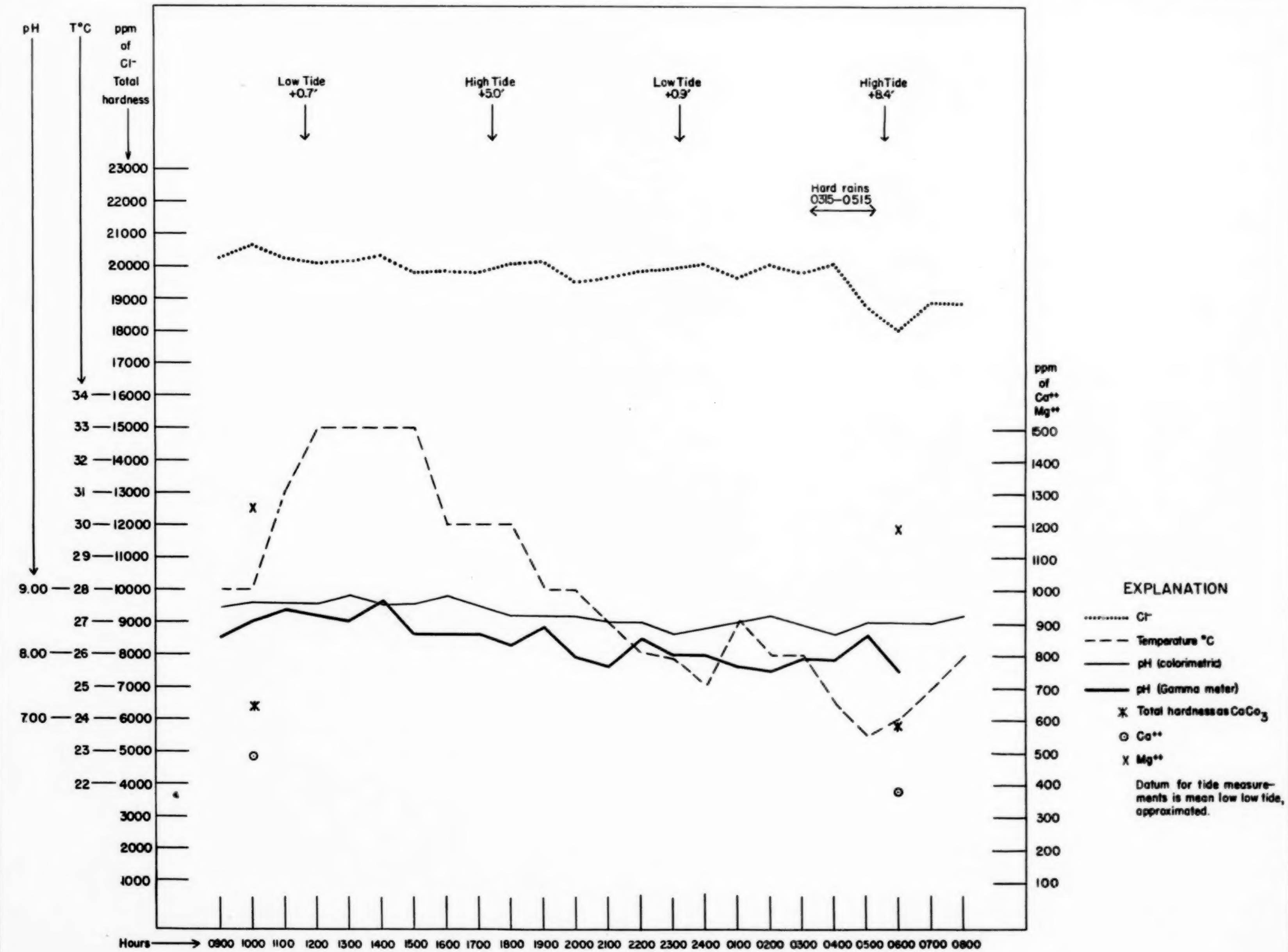



FIGURE 5. PROPERTIES OF SHALLOW WATER IN FLOW OVER WINDWARD REEF FLAT (JULY 6-7, 1951)

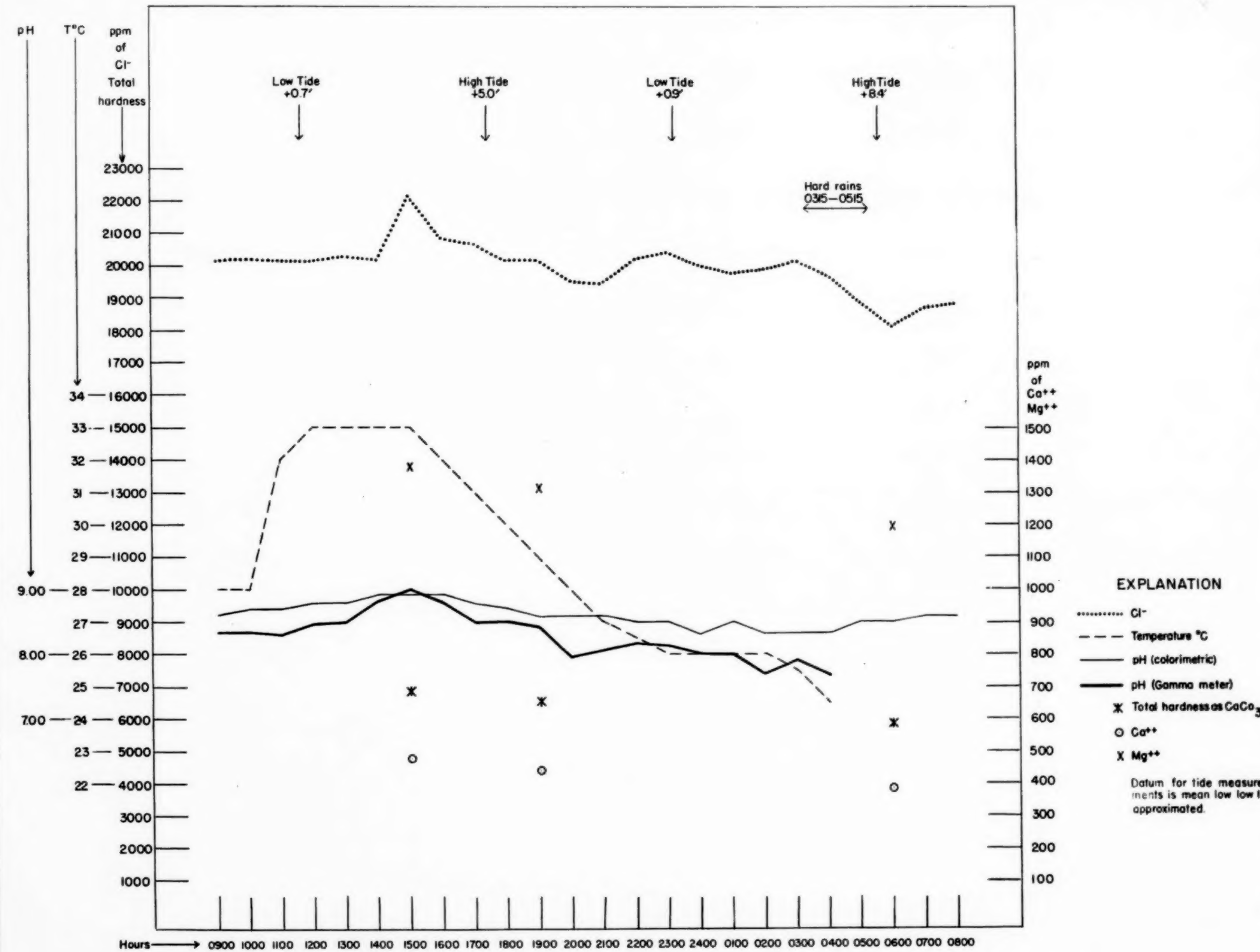



FIGURE 6. PROPERTIES OF WATER IN LOW TIDE POOL OF WINDWARD REEF FLAT (JULY 6–7, 1951)

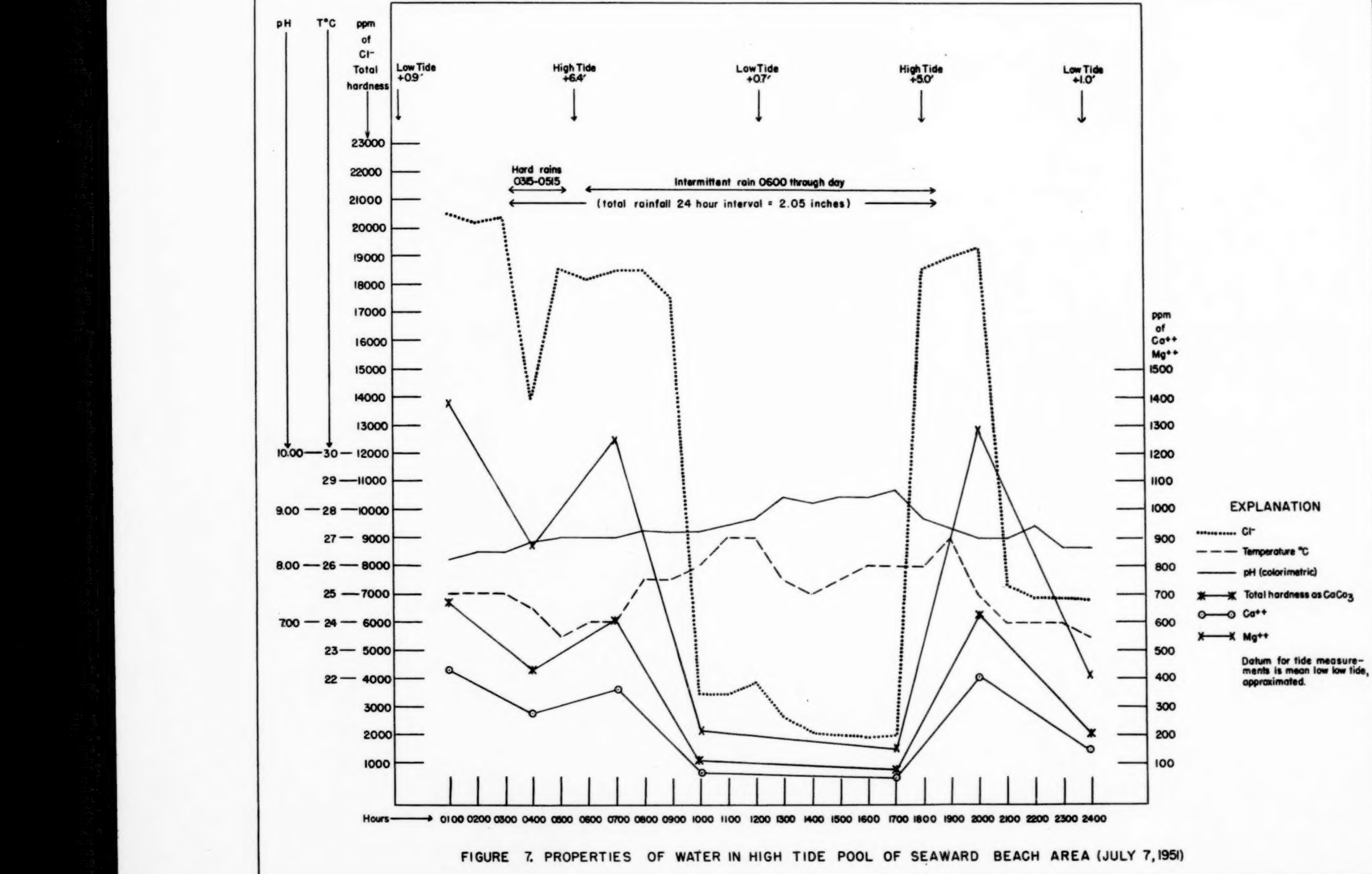



FIGURE 7. PROPERTIES OF WATER IN HIGH TIDE POOL OF SEAWARD BEACH AREA (JULY 7, 1951)

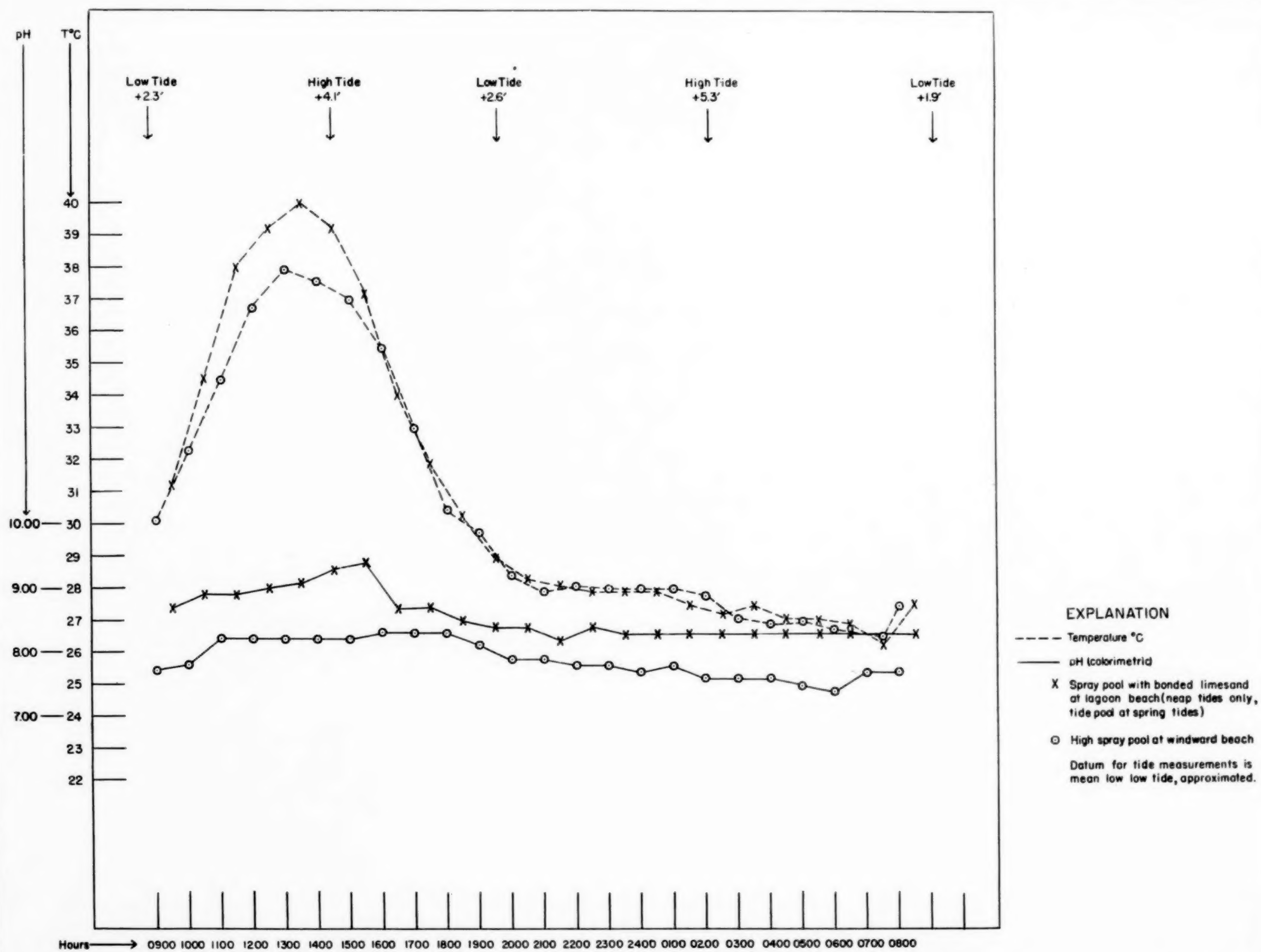



FIGURE 8. TEMPERATURE AND pH OF SPRAY POOLS (AUGUST 27-28, 1951)

| Sample and figure reference | Minimum pH | | | | Maximum pH | | | | Periodic variations of pH | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | high | | | | low | | | |
| | meter | | colori-metric | | meter | | colori-metric | | meter | | colori-metric | | meter | | colori-metric | |
| | pH | time | pH | time | pH | time | pH | time | pH | time | pH | time | pH | time | pH | time |
| Shallow lagoon, fig. 4 | 7.63 | 2330 | 7.9 | 2330 | 8.63 | 1230 | 8.9 | 1130 to 1330 | >8.0 | 0500 to 1900 | >8.5 | 0800 to 2000 | <8.0 | 2000 to 0400 | <8.6 | 2100 to 0700 |
| Windward reef, fig. 5 | 7.75 | 0200 | 8.3 | 2300 and 0400 | 8.80 | 1400 | 8.9 | 1300 and 1600 | >8.0 | 0930 to 1630 | >8.5 | 0830 to 1730 | <8.0 | 1730 to 0530 | <8.6 | 1830 to 0730 |
| Low windward tide pool, fig. 6 | 7.65 | 0200 and 0400 | 8.3 | 2400 and 02-0400 | 9.05 | 1500 | 8.9 | 1400 to 1600 | >8.2 | 0500 to 1900 | >8.5 | 0700 to 2100 | <8.2 | 2000 to 0400 | <8.6 | 2200 to 0600 |
| High windward tide pool, fig. 7 | — | — | 8.1 | 0100 | — | — | 9.3 | 1700 | — | — | >8.4 | 0500 to 2200 | — | — | <8.5 | 2300 to 0400 |
| Windward spray pool (*), fig.8 | — | — | 7.4 | 0600 | — | — | 8.3 | 1600 to 1800 | — | — | >8.0 | 1100 to 1900 | — | — | <8.0 | 2000 to 1000 |
| Lagoon (leeward) spray pool, fig.8 | — | — | 8.2 | 2130 | — | — | 9.4 | 1530 | — | — | >8.3 | 0930 to 2030 | — | — | <8.4 | 2130 to 0830 |

(*) Presence of decaying flesh in pool inferred to account for low pH readings.

Table 4. Variations in pH of shallow marine and beach zone waters

Table 4. Variations in pH of shallow marine and beach rock waters

| Sample and figure reference | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [illegible] | [illegible] | | | | | | | | | | | | | | | |
| [illegible] | [illegible] | | | | | | | | | | | | | | | |
| [illegible] | [illegible] | | | | | | | | | | | | | | | |
| [illegible] | [illegible] | | | | | | | | | | | | | | | |
| [illegible] | [illegible] | | | | | | | | | | | | | | | |
| Lagoon (leeward) spray pool, Fig. 9 | [illegible] | | | | | | | | | | | | | | | |

(+) Pronounced decaying flesh in pool interior, accounts for low pH readings.

| Sample and figure reference | Temperature °C | | | | Chloride (ppm) | | | | Hardness (ppm) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | min. | time | max. | time | min. | time | max. | time | total hardness | $Ca^{++}$ | $Mg^{++}$ |
| Shallow lagoon, fig. 4 | 23.5 | 0430 | 34.0 | 1230 | 18,880 | 0530 | 20,680 | 1330 | 6225 to 6530 | 408 to 486 | 1266 to 1317 |
| Windward reef, fig. 5 | 23.5 | 0500 | 33.0 | 1200 to 1500 | 18,080 | 0600 | 20,680 | 1000 | 5855 to 6375 | 380 to 486 | 1192 to 1254 |
| Low windward tide pool, fig. 6 | 23.5 | 0500 | 33.0 | 1200 to 1500 | 18,080 | 0600 | 22,120 20,880 | 1500 1600 | 5855 to 6855 | 380 to 478 | 1192 to 1375 |
| High windward tide pool, fig. 7 | 23.5 | 0500 and 2400 | 27.0 | 1100 1200 1900 | 1960 | 1600 | 20,480 | 0100 | 735 to 6685 | 46 to 422 | 151 to 1368 |
| Windward spray pool, fig. 8 | 26.6 | 0700 | 37.9 | 1300 | — | — | — | — | — | — | — |
| Lagoon (leeward) spray pool, fig.8 | 26.3 | 0730 | 40.0 | 1330 | — | — | — | — | — | — | — |

Table 5. Temperature, chloride content, and hardness of shallow marine and beach zone waters

by Emery (1946, p. 221, fig. 12) in a southern California tide pool with a temperature range of 14° to 26° C. A pH reading as low as 7.4 was recorded colorimetrically in a high windward spray pool at 6 a.m. and one as high as 9.4 in a lagoonside spray pool at 3:30 p.m.

Importance is attached to figure 7, representing a high seaward tide pool, because it shows an essentially regular diurnal variation curve of pH (colorimetric) through a period of fluctuating temperatures and dilution by rain (2.05 inches rainfall in 24 hour interval recorded on figure 7). Concentration of $Cl^-$ in this tide pool fell 6000 ppm during hard rains from 3:15 to 5:15 a.m. However, it jumped back 4500 ppm with the first flushing wave of the high tide after the rains stopped and was kept at this concentration as long as the tide pool was reached by an occasional high wave. Concentration fell 15,000 ppm during a day of rains but jumped from 2,000 to 19,000 ppm as the tide reached peak and flushed the pool again. Chlorinity fell off markedly again at 9 p.m. as the tide receded and the pool was beyond reach of waves, but this drop must be explained by dilution from accumulated rain water seeping and trickling down from the irregular rock surface above the pool, for there was no rain at this time. Concentration in ppm of $CaCO_3$, $MgCO_3$, $Ca^{++}$, and $Mg^{++}$ varied directly with $Cl^-$, and none of these concentrations showed any relation to temperature of pH.

Clearly, the pH of this tide pool is not significantly affected by or related to either temperature, chlorinity, or any of the variables that change with chlorinity. However, pH, temperature, and chlorinity do vary together in other situations (figs. 4 - 6, 8), and it looks as if they may vary in relation to some common factor. Sunlight provides a suitable common factor for temperature and pH, but its possible relation to the measured variations in chlorinity is not clear. Rain and variation in outflow from the fresh water lens with the tides are probably more important in accounting for chlorinity variations.

The general periodic variations of pH from relatively high during the day to relatively low at night is well broughtout by table 4. During hours of sunlight marine plants (both attached and planktonic) use up $CO_2$ in photosynthesis, causing relative acidity, as measured by hydrogen ion concentration, to decrease, and pH, the inverse measure of hydrogen ion concentration, to rise. The reverse is true at night, when plants are not using $CO_2$ for photosynthesis, but both plants and animals are producing $CO_2$ through respiration. The $CO_2$ content of the water increases, hydrogen ion concentration rises, and pH falls. This is true of the high seaward tide pool, without regard to the extraneous factors that affect chlorinity and temperature, presumably because the variation in pH is organically controlled. Emery (1946, p. 221, fig. 2) clearly shows that diurnal variation of pH in tide pools at La Jolla is inversely related to $CO_2$ concentration. At the same place, he notes that variations in partial pressure of $CO_2$ from greater than in air at night to less than in air during the day indicate a larger range in $CO_2$ actually released and used than is indicated by measurements obtained.

Special interest in the diurnal cycle of pH variation derives from the part that tropical marine waters appear to play in solution and precipitation of $CaCO_3$. On the one hand, it is now common knowledge that such waters are normally saturated or supersaturated with $CaCO_3$ and therefore not capable of taking it into solution. On the other hand, the physical evidence of pitting and undercutting of tropical limestone shores is convincing to some (including myself) that normal tropical marine waters, under some conditions, can dissolve $CaCO_3$. Data obtained at Onotoa substantiate the conclusion already reached by Emery (1946, pp. 225-226) that these conditions are related to diurnal variation of pH in intertidal or very shallow waters with a high biotic density. During the day, $CO_2$ in shallow waters and tide pools is

being used in photosynthesis, pH rises toward a maximum of 8.6 to 8.8 or 8.9[3/] in open shoal water and 9.1 to 9.4[3/] in tide pools and spray pools, and precipitation of $CaCO_3$ should take place. At night, when the $CO_2$ content of these same waters is increasing, pH falls toward a minimum of 7.6 to 8.3[3/] in

---

3/ Highest readings colorimetric and probably in the range of 0.3 high.

---

both open shoal water and tide pools, and it is probably at times of lowering of pH below about 7.8 to 8.0 that solution occurs. Emery (1946, pp. 222-225) has made the necessary calculations to show for similar data, though in a temperature range about 10° C lower, that solution at night and precipitation during the day is in fact possible within the observed range of pH. In arriving at the foregoing figures, data from the windward spray pool of figure 8 are discounted, because this pool was found to contain decaying flesh that doubtless accounts for its low pH. Of course, such things are common in tide pools and spray pools and would account for accelerated solution there.

That the effects of solution in shore zone areas are commonly more in evidence than precipitation is explained by the susceptibility of the minute aragonitic needles of the precipitated $CaCO_3$ to being flushed away by waves--or even blown away by wind at low tide from parts of the reef and tide flats that are exposed long enough to dry. Precipitated $CaCO_3$ in and near the shore zone of Onotoa appears to be preserved only on the elevated rims of certain tide pools and probably as part of the white encrustations on the surfaces of sediment-binding algae. Naturally, rain water, both as solvent and as flushing medium, accentuates the process of pitting and formation of tide pools and spray pools, and the effect of decaying organic matter is also important. However, neither rain nor decaying organic matter can have much

effect on the production of the undercut notches that are so common around limestone islands of the tropical seas.

### Flow of water over the windward reef

The movement of powdered fluorescein marker dye was observed at several places over the reef flat, in surge channels, and over the benched reef slope seaward of the reef front along the windward shore near Government Station. Observations were made during a receding tide at a time of moderately strong surf, and all time intervals and quantities of dye were estimated.

About midway of the reef flat, which is about 800 feet wide here, a patch of dye about 20 feet in diameter on application spread out to about 80 feet wide by 100 feet long (elongated normal to shore) and moved altogether past the point of application in about 30 seconds. It then surged inward and outward with onshore surge and recession of waves but sinking as it moved and with dominant movement seaward along the bottom. Within about 10 minutes after application the dye was foaming in the surge channels of the coralline ridge.

About half a cupful of the powdered dye was applied just behind the coralline ridge and then observed from a raft anchored about 110 feet beyond the ridge on the benched reef slope. Traces of this dye foamed in the upper waters of the surge channels for a long while, but the bulk of it continued to sink and drift seaward for about 30 minutes. It gradually worked down to a basal layer of water and streamed out over the seaward sloping bench.

Dye was added to surface water about 50 feet seaward of the coralline ridge and surge channels. This dye worked outward and downward, streaming to the bottom at about a $30^{\circ}$ angle in about 5 minutes. Within about 15 minutes it was all seaward of the shelf.

About three-quarters of a cupful of powdered dye was released at the bottom of a 6- to 8-foot-wide surge channel near its midlength, in about 10 feet of water. This dye surged up and down and spread to adjacent grooves, but it stayed in the surging waters for about 10 to 15 minutes before beginning to stream definitely seaward. It then streamed outward and downward across the sloping bench.

The foregoing observations show that there is a definite outward-moving bottom current in the shallow water over the reef flat and upper reef slope, at least at times of receding tide. Time did not permit repetition of the observations with an incoming tide, but I would expect the same pattern--the water that runs onshore at the surface because of the breaking waves must move offshore at the bottom. The fact of most importance is that this current is downward as well as outward, literally dragging the bottom, and at times of outflow between swells at the reef margin its force is memorable. Moreover, as this movement is perceptible even beyond the reef front at times of only moderately strong surf, it is probably considerable during storms. This is of importance in connection with the origin of reef front grooves and surge channels.

[illegible]

[illegible]

## ORIGIN OF REEF-FRONT GROOVES AND SURGE CHANNELS

The fronts of most organic or limestone reefs that are exposed to the sea somewhere show a comb-tooth pattern of closely spaced grooves that are separated from one another by rocky buttresses. The parts of these grooves that transect the surf zone (and the coralline ridge if one is present) are called surge channels (Tracey et al, 1948, p. 867).

The origin of these groove-and-buttress systems is a vexing question, for they show features attributable to both biogenic construction and mechanical erosion. Ladd and others (1950, p. 413) have emphasized the importance of outgrowth of algal spurs to form the buttresses at Bikini atoll. They believe that although there probably "is mechanical abrasion during periods of exceptionally heavy weather...this does not seem adequate to explain the grooves as erosional figures." David and Sweet (1904, p. 81) explained them by a hypothesis of combined growth and erosion factors and Kuenen (1933, p. 80-81) believed that they were mainly constructional.

Newell et al (1951, p. 25), with reference to the Bahama Islands, inclined to the view that "the grooves are cut," and to judge from the fact that the grooves observed by them "are incised in oölitic country rock they evidently are erosional features." Before learning of Newell's views, studies of grooves and surge channels on Onotoa and previous observations of similar features on Guam, Saipan, and elsewhere had lead me to recognize erosion as important in the formation of the grooves. I have also seen, but not studied, grooves similar in plan to more conventional surge channels in the face of a basalt-floored bench just west of Haena point in northwestern Kauai, of the Hawaiian Islands.

In my opinion the grooves in many places are initially cut by outflowing undercurrents that carry tools of abrasion not available to the more spectacular inrushing surf. This produces the characteristic radial pattern of gravity flow. It is further suggested that most of this cutting followed falls of sea level, when reduction of bench surfaces provided maximum quantities of detritus for abrasion. Under proper light conditions air photographs of some shores (e.g., north Saipan) show several levels of offshore and even elevated grooves, not closely matching at their boundaries. These indicate groove-cutting at successive stands of sea level related to bench formation. Once a bench is reduced to equilibrium level, however, growth factors become relatively important. The abraded upper sides and crests of spurs then become veneered with growing coralline algae and corals, and the grooves may be masked over and generally closed or partly closed at the surface. This produces under-reef caverns and blowholes. Growth of algae and corals subsequent to groove cutting may be so extensive as to mask completely the evidences of abrasion, but the grooves and surge channels are found at so many places, and the radial pattern is so like the normal gravity pattern found on rilled rock beaches and elsewhere, that abrasion by outflowing gravity currents probably determined the basic pattern at many places where organic growth is the prevailing modern feature.

Many grooves and surge channels observed on Onotoa and elsewhere are undercut at their basal sides and floored with gravel, and many on the leeward coast of Saipan end in submarine potholes containing coarse gravel. The grooves are ordinarily most abundantly developed on windward reefs, but they have been observed in all quarters of the wind and at places are common on leeward reefs. Their degree of prominence is believed to be controlled by

strength of outflowing current, and thus surf, and by quantity of abrasive materials in transit. On the other hand, there are places where growth alone may produce the comb-tooth pattern. Both mechanical erosion and organic growth must be considered important in the origin of groove-and-buttress systems, the part played by each probably varying according to local conditions.

On Onotoa the grooves of the windward reef are almost limited to the surf zone and are thus synonymous with the surge channels, but traces of them run across the benched slope of the upper reef, masked by coral growth and debris. The front of the reef at the landward side of this bench is about 12 feet high and from the seaward side looks like the truncated spur-and-canyon topography of a steep-fronted and flat-topped mountain range or plateau. The surge channels range in length from about 50 to 80 and rarely as much as 120 feet. They are about 6 feet deep at midlength, and deepen gradually to about 8 feet at the reef front, with a downward dip of another 2 to 4 feet as they pass beyond the wave-breaking front of the reef. They range from 2 to 8 feet in width at the reef front and are undercut up to 1 foot on each side at their bases. Living algae and corals are abundant only at the crests and upper sides of intervening buttresses. The surge channels are floored with very coarse, mostly slabby gravel. At the reef front above this gravel during a period of relatively strong surf (swell measured 6 feet high, combers averaged an estimated 8 feet), the only movement experienced was an up and down with the swell. Down in the lower part of the channels, however, the swimmer is carried back and forth with the surge for as much as 15 to 20 feet at a time. Under these conditions only small pieces of the gravel were observed to move, the maximum size observed in movement being a slab about 8 inches in diameter that rocked gently back and forth without being transported from its original position. Slabs this size and larger, although well rounded, are mostly

coated with a fairly luxurious felt of living green algae, and it is evident that their rounding occurs only at times of storm or very heavy surf, with plenty of time between for growth of algae. Whereas there is apparently enough movement of the boulders and smaller gravel and sand to prevent growth of coral and coralline algae on the floor and lower parts of the surge channels (except locally at their mouths), the grooves are probably not being significantly enlarged at the present time.

It is suggested that most of the groove cutting in the reef front at Onotoa occurred during beveling of the present reef flat after the recent 6-foot eustatic fall of sea level.

On Onotoa, evidence for Recent lowering of sea level of the order of 5 or 6 feet is found in remnants of an elevated _Heliopora_ reef flat that occurs up to about 2½ feet above the inner edge of the reef flat, both on the beach and in wells (e.g., profile 5, fig. 3). The inner edge of the reef flat, in turn, is estimated to be 2 to 3 feet above present mean low low tide. At present the upper limit of living _Heliopora_ flats is about at low tide level. Similar occurrences of relatively elevated _Heliopora_ flats are also found at Funafuti (Sollas, 1904, pp. 21-24; David and Sweet, pp. 67-68 and plates). Further evidence of a fall of sea level of about 6 feet at Onotoa is provided by elevated cobble stripes of a sort that I have observed only on reef flats. These cobble stripes rise about 2 or 3 feet above a surface of cobble gravel that is about 6 or 7 feet above the present reef flat at the northwest end of Onotoa and are separated from the lower-lying present reef flat by a gravel rampart.

As a Recent world-wide 6-foot fall of sea level may be amply documented, the evidence on Onotoa is only part of the broad picture. The higher stand from which the present sea has receded is provisionally attributed by Stearns (1941, p. 780) to the postglacial optimum temperature cycle of 5000 to 7000 years ago, when water previously and now tied up in the polar ice caps was in the ocean. Fall to present sea level probably took place in two steps, the first a 3- or 4-foot drop and the second 2 or 3. Evidence for the second drop consists of a bench about 2 or 3 feet above the present reef flat at Onotoa and elsewhere (see Kuenen, 1933, pp. 66-70; Dana, 1872, pp. 333-346). No attempt will be made here to summarize the large literature on the question of recent eustatic falls of sea level.

Atoll islands characteristically consist of unconsolidated debris resting on a solid foundation. This foundation must be broad enough and high enough so that this unconsolidated debris can accumulate beyond the reach of strong wave action and be preserved there. The foundation may consist of a reef that has grown to the surface of the sea, or which, having grown to the surface, is left somewhat above normal sea level by recession of the sea.

On a surface which is exposed between tides, lime-precipitating and sediment-binding green and blue-green algae flourish, and even coarse clastic materials are quickly and firmly bonded together by interstitial calcium carbonate. This is demonstrated by the cementation of blocks in the stone-ring fish traps on the outer reef flat and by firmly welded bars of boulder conglomerate at Aonteuma and at the northwestern extremity of the atoll. Upon such an intertidal surface, also, debris tossed by the waves has a good chance of remaining in position at a distance from the reef front that varies with the transporting power of storm waves.

The first step in the building of an atoll island, then, is the erection by storm waves of a ridge or rampart of coarse gravel on a living reef flat or wave-cut bench. Seaward additions may, of course, be made to such a rampart by subsequent storms. However, evidence that the structure is essentially stable along a given line and under prevailing strength of waves is found in the fact that the gravel rampart is a single ridge at most places.

Building of land on the lagoon side of this rampart is harder to understand. That much of the work is done by wind is evident from the prevalence of dune sands at many places, but from where does the sediment come? In the sands of Onotoan islands it is clear from the abundance of the reef-flat dwelling foraminifer <u>Calcarina</u> that much if not most of the sand is derived

from the reef. The tests of _Calcarina_ and other Foraminifera that inhabit the algal mats of the reef flat apparently were washed across the reef and drifted around the ends of and along the lagoon side of the gravel rampart by local currents. The washing of water across the reef through breaks in the rampart is a sufficient explanation of the currents, but they may be locally emphasized or negated by other factors, such as wind. In the job of island building these currents will be aided by wind-borne sand from tide flats or from bars produced by the currents along the growing shore in the lee of the gravel rampart.

The island should continue to grow in width as long as there is a base for it to spread lagoonward on and a supply of sediment for building. The latter is provided by Foraminifera and clastic particles of $CaCO_3$. Eventually, if the process continues, and currents do not keep the lagoon swept free of sediment, the lagoon must fill up and a large land area develop, as at Christmas Island, in the northern Line Islands. The height of an atoll island, insofar as it is not attributable to fall of sea level or to rampart building, depends on the height to which wind can build dunes on the base provided and from material at hand. Most atoll islands are relatively narrow and low, seldom anywhere exceeding 12 to 18 feet above the reef flat. In my opinion this indicates that they are also relatively modern phenomena. Several authors have suggested that the building of atoll islands has been accelerated by and perhaps dates from the Recent 6-foot eustatic fall, and such an interpretation would help to explain much of what is known of these islands, their biotas, and human migration in the Pacific. This recession of sea level would have resulted in an apparent elevation of near-surface reefs, providing excellent bases for land construction of the type the atoll islands show.

The common presence of a lengthwise depression or depressions within atoll islands is explained by the outlined manner of growth. In the early stages of the process the currents from the ends of the islands would tend to swing a little away from the gravel rampart and build a longshore bar on the lagoon side. Subsequent additions are made mainly to the lagoon side of this longshore bar, and sediment is added to the depression areas only as it may blow in or wash over bar or gravel rampart. On Onotoa the inner depression is only locally present. However, the process that results in an inner depression is perhaps exemplified at both ends of the atoll islands by the arcs of land whose sandy extensions curve around tidal inlets (fig. 2). The general pattern of distribution on Onotoa of sand toward the lagoon and gravel toward the sea, and of islands mainly to windward, also is consistent with the patterns of other atolls and with the process suggested. Storms that either washed across or broke through the gravel ramparts or swept in gravel from the lagoon may be called upon to explain gravel deposits lagoonward of the rampart. Stages in island growth, according to the scheme outlined, seem to be illustrated by the longitudinally paired island strips of Marakei Atoll in the Gilberts (Agassiz, 1903, pls. 149-150) and by the filling since 1900 of lakes in the central depression of Putali Island on Addu Atoll in the Indian Ocean (Sewell, 1936a, p. 77). Sewell also shows (loc. cit.), by reference to pumice lines, that "the inner beach of the island has advanced toward the lagoon by some 10 yards" between about 1885 and 1934.

The gravel rampart itself is commonly capped and at places completely concealed by a veneer or thick cover of fine-grained younger dune sands, blown ashore from the reef-flat area so recently as to show no humus layer, or thinly to veneer a humus layer below. This sand contains few Foraminifera and

is thought to be mostly derived at times of low tide from the fine $CaCO_3$ particles that adhere to the drying surfaces of the green and blue-green algae of the inner reef flat. The probability that even extensive windward beach-zone dune belts cap gravel ramparts seems strong enough to warrant the showing of inferred ramparts beneath such dunes on the island profiles of figure 3.

If the islands of Onotoa were mainly built on a platform residual from the 6-foot stand of the sea, and if this stand of sea is properly correlated with the postglacial optimum, all of these land-building events have taken place in about the last 4,000 to 7,000 years.

Atoll islands appear to be eroded primarily at times of great storms by breaching of islands or by the complete removal of islands and other sediments on stretches of the reef flat. If at least the seaward portions of the unconsolidated atoll sediments rest on a bench surface at a higher level than the reef flat, as at Onotoa, destructive processes should be retarded. Remnants of beach rock on denuded reef flats and buried or outcropping beach rock within land areas provide the best basis for reconstructing stages in the building and erosion of atoll islands, once given a foundation.

## SHIFTS OF SEA LEVEL AND THEIR EFFECTS ON MODERN REEFS

The reef flats of Onotoa on which islands are situated are truncated surfaces. Green algae thrive on the inner reef flats. A few corals and abundant red algae are found on their seaward portions. Evidence that this surface has been truncated is found in the elevated Heliopora flat that dips under the islands. This surface is continuous, at places observed carefully, with an old, truncated Heliopora flat that runs across the present reef and is merely veneered with algae and the sediments which they bind and cement to rock. Evidence of a former stand of the sea about 6 feet above present sea level is found in the elevated area of reef-flat cobble stripes at the northwest end of Onotoa, and also in the elevated and truncated surface of the old Heliopora reef.

At Arno Atoll, in the southeastern Marshall Islands, coral growth flourishes at least on many parts of the reef flat. Of this atoll Wells (1951, pp. 4-5) has stated that there is no evidence of fall of sea level, and the same is commonly reputed to be true of atoll islands. On the other hand, evidence of fallen sea level has been recorded at Bikini (Ladd et al, 1950, pl. 4, p. 413), Funafuti (David and Sweet, 1904, p. 67-68), and Horsburgh atolls (Sewell, 1936b, p. 121). Regardless of the fact that independent confirmation cannot everywhere be found, there is widespread and impressive evidence not only of a recent 6-foot eustatic fall of sea level, but of a very recent fall of roughly 1½ to 3 feet and of one or more former sea levels in a range of 16 to 35 feet above the present one (Daly, 1920; Daly, 1926, pp. 174-179; Kuenen, 1933, p. 66-70; Stearns, 1941, p. 779-780; Stearns, 1945). The 16- to 35-foot zone is obscure, and its effects on modern reefs can only have involved shoaling preparatory to later events of

more significance to their present aspects. The $1\frac{1}{2}$- to 3-foot fall seems best considered as a temporary stand in the lowering of the sea from the 6-foot level. There have also been local and perhaps eustatic positive movements of sea level, but positive eustatism for any given level is hard to demonstrate and relates only indirectly to the question here considered.

The evidence at hand suggests that the present superficial aspects of reefs are related to whether their surface was within 6 feet of sea level at the time of the 6-foot eustatic stand. If they lay below 6 feet, the drop in sea level would not have affected them markedly, and, if not sites of islands, they would presumably be flourishing organic reefs today. At such places no evidence of eustatic fall would be found except, in an indirect way, islands themselves, the construction of which would be facilitated by the shoaling of their potential foundations. If the surface of a reef were within 6 feet of sea level at the time of the 6-foot eustatic stand, it would be abraded and truncated with fall of the sea. It would be an area poor for growth of corals and crustose coralline algae, and veneered with clastic debris and soft algae or articulate corallines. Such reefs are found at Onotoa, Taraw, and Butaritari in the Gilbert Islands as well as in many other parts of the Pacific. In my opinion they are in themselves evidence of recent fall of sea level. Of course, it is to be expected that nontruncated reefs will be found in areas of truncation, for it is highly unlikely that all reefs of a given area or all parts of a given reef would have grown to uniformly shoal depths prior to the 6-foot fall.

A second feature of interest in connection with the Recent 6-foot fall of sea level is the already discussed development of grooves and surge channels in the present reef rim. It is here considered that such features at many or most places originally result from abrasion by gravity currents flowing

outward across the reef and equipped with abrasive tools provided by truncation of a relatively elevated reef flat. When such a reef flat is reduced to a stable level, or before, if conditions are favorable, growth of coralline algae and corals at the beveled reef margins is accelerated and eventually masks or even eradicates evidences of abrasion. The east end of Tarague Beach, at north Guam, is believed to exemplify an elevated bench in process of such reduction. For some unknown reason it, alone of all reef-flat areas seen on Guam, preserves numerous remnants of the older level between grooves that extend across the entire reef flat--as, of course, they should do until such time as lateral cutting processes reduce them to a general level.

A corollary of the contention that the 6-foot eustatic fall exerted a controlling influence on the superficial aspects of modern organic reefs is that one should be able to state, from the nature of its surface, whether or not any given reef area was within 6 feet of sea level at the time of the 6-foot eustatic stand. If it is sparse in living coral and veneered with green algae and clastic debris, and particularly if it is also a relatively smooth surface, it was probably truncated. If coral growth is vigorous and the surface irregular, it was probably not within 6 feet of the old sea level, or else it has grown up from a very severely beveled reef margin.

## APPENDIX A--LIST OF REEF BUILDING CORALS AND HYDROZOANS

For the following preliminary identifications of corals and reef building hydrozoans from Onotoa I am indebted to Dr. J. W. Wells. The list given is composite for all localities and environments collected. Altogether it includes 26 genera and 50 to 60 species of corals and 2 genera and species of hydrozoans.

### Scleractinia

Acropora humilis (Dana)

Acropora spp.

Astreopora sp.

Coscinarea columna (Dana)

Culicia

Cyphastrea micropthalma (Lamarck)

Echinophyllia aspera (Ellis and Solander)

Echinophyllia sp.

Echinopora lamellosa (Esper)

Favia stelligera (Dana)

Favia spp.

Favites sp.

Fungia concinna Verrill

Fungia scutaria Lamarck

Fungia valida Verrill--a new record

Goniastrea pectinata (Ehrenberg)

Goniastrea retiformis (Lamarck)

Halomitra philippinensis Studer

Herpolitha limax Esper

Hydnophora microconos (Lamarck)

Hydnophora rigida (Dana)

Leptastrea purpurea (Dana)

Lobophyllia sp.

Merulina sp.

Montipora caliculata (Dana)

Montipora foveolata (Lamarck)

Montipora verrucosa Lamarck

Montipora spp.

Pavona clavus (Dana)

Pavona varians Verrill

Pavona sp.

Platygyra rustica (Dana)

Platygyra sinensis (Edwards and Haime)

Plesiastrea versipora (Lamarck)

Plesiastrea sp.

Pocillopora caespitosa Dana

Pocillopora damicornis (Dana)

Pocillopora danae Verrill

Pocillopora elegans (Dana)

Pocillopora meandrina Dana

Pocillopora modumanensis Vaughan?

Pocillopora spp.

Porites andrewsi Vaughan

Porites lichen Dana

Porites lobata Dana

Porites lutea Edwards and Haime

Porites superfusa Gardiner

Porites spp.

Psammocora (Plesioseris) sp.

Seriatopora hystrix (Dana)

Tubastrea

Alcyonaria

Heliopora coerulea (Pallas)

Hydrozoa

Millepora tenera Boschma

Stylaster sanguineus Edwards and Haime

# APPENDIX B--DESCRIPTION OF ECOLOGIC FIELD UNITS

Recognition of contiguous ecologic field units within a given general environment amounts to designating segments of a continuously variable sequence. Such units in large part express real central tendencies, but their boundaries are mostly indefinite, and to draw boundaries at all may be misleading. How to define the particular continuous variables in question and express them suitably on a map without recognizing suites of intergrading units is a problem yet to be satisfactorily solved. Pending such solution, or a reduction of categories on completion of laboratory studies and reevaluation of field data, the following descriptions may give the interested reader a more particular idea of the ecology of Onotoa.

## Islands

### Dune limesands

Younger dune sand. Mostly fine- to medium-grained, angular $CaCO_3$ sand. Humus layer incipient, thin, or absent.

Older dune sand. Similar to "younger dune sand," but with humus layer weakly to moderately well developed. In part rich in tests of foraminifer *Calcarina*.

Indurated dune sand. Indurated phosphatized (?) older dune sand.

### Limesands other than known dune deposits

(Gravel intervals locally included in all types. Generally comprising most arable land and supporting thickest vegetation on Onotoa.)

Younger limesand. Fine- to coarse-grained sand, with humus layer thin or absent; locally includes gravel and wind-blown sand. According to local reports, the area of younger limesand and gravel on the point at Tabuarorae has been built since 1900.

Calcarina limesand. Sand of which 50% to 99% of the individual grains are tests of the foraminifer Calcarina. Generally with well-developed humus layer. Forms loose, well-drained soil with good capillary system. Favored for taro pits and breadfruit where ground water is sufficiently fresh.

Gravelly limesand. Sand with less than 50% Calcarina and with intermixed shelly gravel (abundant small Cardium, etc.) and small-pebble gravel.

Undifferentiated limesand. Fine- to coarse-grained sand with generally well-developed humus layer, with less than 50% Calcarina, and with little or no shelly gravel.

Limesilt grading to limesand. Mapped only in low, permanently damp areas. Generally wet and stiff. Humus layer poorly to moderately well developed. At places encrusted with caliche-like hardpan. Supports salt-tolerating shrub Pemphis (As well as poor coconuts, sparse Pandanus, etc.). Favored for retting pits because generally brackish water lies close to surface.

## Limegravels
(Intervals of mostly angular sand locally included in all types)

Elevated flat-cobble stripes. Low ridges or stripes of cobbles oriented normal to beach line, similar to ridges that develop on modern gravel-veneered reef flats. No humus, few fines. Stripes are about 3 feet high, and bases of troughs between them are about 6 feet above present reef flat (hand level data). This is taken as evidence of a recent relative elevation of about 6 feet and correlated with the now well-documented Recent world-wide 2-meter eustatic fall of the sea.

Coarse coralliferous gravel. In part composed of large meandriform and astraeiform coral heads. Has little or no humus and few fines. Grades to "coralliferous pebble gravel."

Coralliferous pebble gravel. Fragments of branching Acropora conspicuous--also includes Heliopora and other corals, corraline algae, and mollusk shells and fragments. In coarser range grades to "coarse coralliferous gravel" and at many places includes areas or intervals of such gravel. In finer range grades to sands by increasing proportion of fines and reduction in size of gravel, and in such places approaches soil and vegetation characteristics of limesands.

## Caliche

Caliche. Caliche-like limestone, not similar to beachrock. Found at one locality about 3 feet above reef flat level and behind sea-facing boulder rampart (north end of northern large island). Very thin crusts of caliche also occur at the surface of the enclosed Pemphis flats near this locality and in low places that are floored with wet limesilt.

## Land bound areas of permanent brackish water

Brackish water ponds. Maximum depth 3 to 4 feet, blue-green algae abundant.

Blue-green algae flats. Areas of very fine $CaCO_3$ sediments rich in moderately to slightly brackish water cover nowhere exceeding 1-foot depth at normal tide level and in places barely enough to keep the ground wet. Covered with cauliflower-shaped nodules or mats of sediment-binding and lime-secreting blue-green algae.

## Intertidal environments except reefs

### Unconsolidated beach

Includes sand beach, gravel beach, sand and gravel beach, boulder beach, and outer beach.

Outer beach. Sand beach off lagoon side of southern main island that extends

beach proper beyond normal tide range and is exposed only at low low tides. Similar to "limesand flats" but narrower and sloping $3^{\circ}$ to $5^{\circ}$.

Rocky beach
(Some units described here also occur inland and above normal tide range)

Concordant beachrock. Conformable with present beaches and certain tide flats. In large part little eroded, but commonly rilled and pitted with tide pools. Comprises limesandstone with dips $5^{\circ}$ to $7^{\circ}$ lagoonward on lagoon beaches and nearly horizontal on protected tide flat areas. On sea-facing beaches is limesandstone or coralliferous and algal conglomerate dipping $7^{\circ}$ to $10^{\circ}$ seaward.

Nonconcordant beachrock. Greater age than "concordant beachrock" suggested by occurrence at abnormally high levels, marked unconformity with present beach orientation, or unusually high degree of solution pitting in well indurated limesandstone. As mapped, probably in part includes "elevated reef-flat rock."

Bonded limesands. Weakly to strongly bonded limesands, commonly with a surface felt of sediment-binding (and lime-precipitating?) blue-green algae. At places consisting of successive layers separated by thin films of chlorophyll-rich sand that mark former exposed surfaces. Genera of algae provisionally identified from bonded limesands in the field by Dr. Edwin Moul are Chroococcus, Gomphospheria, Gleocapsa?, and other genera of the Chroococales, as well as Lyngbya and Scytonema. At places the bonded limesands show aberrant dips, some up to $30^{\circ}$ landward, where they apparently have formed as depression fillings or perhaps slumped into cavities by collapse from beneath.

Elevated reef-flat rock. Old Heliopora-flat rock or rock consisting of fragments of coral and coralline algae in limesand matrix. The matrix may be partly or entirely a beachrock, but it lacks dip, is unbedded or very obscurely bedded, and is thus more suggestive of indurated reef-flat detritus.

Enclosed intertidal flats

Enclosed limesand, limesilt, or limemud tide flats. Fiddler crab (Uca) borings abundant, and odor of $H_2S$ commonly strong in freshly exposed sediments. Permanently damp and saline, but flooded only at highest tide. "Mud" is used provisionally and in the sense of probable grain size only; it has not yet actually been determined that any of this material is a limemud.

Pemphis flats. Similar to "enclosed limesand, limesilt, or limemud flats," but with cover of the salt-tolerating shrub Pemphis. Found at shoreward margins of "enclosed flats." The shrub Pemphis, of course, also grows upon the land itself, at the edge of the beach or even inland in low places that are subject to periodic flooding or where the ground water is brackish.

Mangrove flats. Similar to "enclosed limesand, limesilt, or limemud flats," but with cover of the mangrove Rhizophora. Generally flooded at same stage of all tides, but mostly "dry" at lowest low tides. Sediments generally in the limemud to limesilt size range and high in $H_2S$.

Mainly intertidal flats adjacent to lagoon proper
(Units under this heading grade to lagoon, reef, and beach units)

Coral-algal rock flats. Dead coral-algal bottom veneered to a large extent with limesand and with local pockets where the sand is thick. Displays

occasional concentrations of the turtle grass Thalassia (and mostly unattached Microdictyon) and in areas of standing water, sparse living coral that consists mostly of stubbily branching Acropora, Pocillopora, and smallish, hassock-like Porites.

Coral-algal rock and sand flats with Zoanthus. Similar to "coral-algal rock flats" just described, but with sand veneer somewhat more conspicuous and supporting extensive growths of the colonial anemone Zoanthus as well as considerable numbers of varied green algae.

Limesand flats. Relatively "clean" sand-covered tide flats, with generally sparse megafauna of burrowing sipunculid worms, ghost crabs (Ocypode sp.), the snail Polynices, occasional cones and terebras, and, at places, the anemone Zoanthus and the common holothurian Holothuria atra Jager. Plants are scarce, but algae occur locally on erratic rocks, and Enteromorpha has been tentatively recognized. Zone extends beyond beach proper to the zero fathom line (mean low low tide) or slightly deeper.

Sand and gravel flats. Tide flats of calcareous sand and gravel with green algae resembling Cladophora and Cladophoropsis, Dictyosphaeria, and Valoniopsis abundant in portions that remain wet at normal low tide. A few living corals are present locally.

Sand and gravel flats with coral. Similar to and grading to "sand and gravel flats" just described, but with scattered living coral, chiefly hassock-like Porites. Invariably wet when seen, and presumably water-covered except at lowest low tides.

Cobble gravel flats. Cobble-veneered areas mostly lagoonward from reef flats, including occasional boulder or pebble fractions. Components mostly angular. Unit also includes indurated cobble conglomerate flats, adjacent to or continuous with reef flats (as adjacent to Aonteuma and at north end of reef flat beyond this islet).

Pebble gravel flats. Areas veneered mainly with pebble gravels, but with some cobbles. Individual coarse fragments primarily angular.

Beachrock ribbed tide flats. Low ridges of old beachrock interspersed with dirty limesand flats, incipient beachrock patches, and circular patches of *Thalassia* (and *Microdictyon*). The common sea cucumber *Holothuria atra* Jager very abundant locally in pools and permanently wet depressions.

Bars and spits

(Continuously exposed or inundated only at highest high tides)

Includes sand bars and spits, pebble gravel bars and spits, boulder gravel bars, and bars of sand and gravel.

Outer reef

Grooved reef slopes. Upper slope of either leeward or windward reef front marked with conspicuous grooves normal to reef front and separated by buttresses veneered with living coral.

Papillated reef slopes. Upper slope of leeward reef front papillated with scattered, but more or less linearly arranged, patch reefs of living coral and coralline algae.

Benched reef slope. Upper slope of windward reef front, comprising a bench that slopes about $15^\circ$ seaward from a depth of about 2 fathoms to the upper part of a $30^\circ$ to $40^\circ$ undersea slope at about 9 or 10 fathoms. Bench generally veneered with a mat of living and dead coral, the predominant types being stoutly branched *Pocillopora elegans* (Dana).

Reef front. Coralline ridge and surge channels prominent on windward side, but ridge is weak or absent on leeward side. The coralline ridge is low, purplish-red in color, and thickly crowded with masses and crusts of coralline algae such as *Porolithon* and *Goniolithon*. It runs along the

surf edge of the reef, is exposed at low tide, and is intersected by numerous channels through which surges the white water of the breaking surf. Presumably it was casual view of this reef front that led Setchell (1928, p. 1840) to state "the atoll of Onotoa...was composed, so far as visible, entirely of nullipore...largely if not entirely...Porolithon craspedium (Foslie) Foslie."

Red alga zone of windward reef flat. A permanently wet area of red algal growth landward from reef front. The outer part or subzone, an area of permanent standing water and locus of tidal fish traps, is called the back ridge trough. Here are scattered cabbage-shaped and branching masses and crusts of coralline algae such as Porolithon and Goniolithon and scattered large living heads of astraeiform and meandriform corals, as well as stubbily branching Acropora and Pocillopora. The green algae Caulerpa and Halimeda are found locally and sparsely in the back ridge trough. The inner part, or Jania subzone, of the red alga zone slopes up and grades to the green alga zone of the inner reef flat, their point of juncture being approximately defined by the inner edge of the fish traps. Biota of the Jania subzone dominated by articulate coralline Jania, with living Foraminifera of the genera Calcarina and Marginopora locally abundant. At places Jania subzone shows scattered, rolled coral boulders up to 16 inches in diameter, these boulders probably being broken loose within the back ridge trough.

Green alga zone of windward reef flat. Inner reef flat characteristically matted with green algae. Commonly divisible into outer, middle, and inner subzones. In the outer subzone the red alga Jania is an abundant holdover from the red alga zone, but green algae predominate. The intermediate subzone is one of flourishing green algae, and the inner

subzone is one wherein the green algae are whitened by encrusting bonded sediments or at places absent from the bare dead coral-algal rock below. At a distance these subzones seem sharply defined because of color differences, but they actually intergrade over rather wide intervals. Characteristic genera of algae throughout the green alga zone include Cladophora or Cladophoropsis, Valoniopsis, and Dictyosphaeria. At many places this zone is strewn with scattered, rolled meandriform and astraeiform coral heads up to 16 inches in diameter, these boulders probably being derived from the back ridge trough of the red alga zone.

Leeward reef flats. Lagoonward portion generally dominated by green algae; seaward portion characterized by abundance of articulate coralline Jania, crustose corallines, and scattered sturdily branched Acropora and Pocillopora.

Gravel and sand veneered reef-flat areas. Dead or decadent reef flat veneered with angular gravel of pebbles, cobbles, or boulders, and with a conspicuous fraction of sand. Living corals few.

Cobble and boulder veneered reef-flat areas. Dead or decadent reef flat veneered with cobbles and boulders. Sand inconspicuous.

Flat-boulder veneered reef-flat area. Chaotic coralliferous flat-boulder gravel on windward reef flat.

Gravel veneer on dead reef-breccia. Rough, angular, coralliferous cobble-pebble gravel with some boulders. Veneers surface of coral debris breccia that presumably represents old reef flat. At places old reef-breccia is bare, with no veneering gravel. Mostly covered only at high tide. Developed primarily between the two main islands.

Calcarina-Marginopora reef-flat areas. Protected reef-flat areas matted with living Foraminifera of the genera Calcarina and Marginopora, and with green algae, the Foraminifera commonly entangled in the algae. Scattered boulders and cobbles are common locally. A few specimens of the common black sea cucumber Holothuria atra Jager are found in permanently wet pockets.

Heliopora reef zone. Living Heliopora in essentially continuous and generally thickly arborescent reef growth, with Acropora and Porites secondary and other coral types minor.

Porites reef zone. Living reef area dominated by large flat-topped heads of Porites. Irregular coral growth on bottom having depths of several feet at low tide.

Acropora-Pocillopora reef zone. Living reef area of varied coral types dominated by varieties of Acropora and Pocillopora; corals thin out from reef flat toward lagoon or tide flats with increase in area of limesand bottom.

Varied reef zone. Reef area of abundant to scattered living coral growth of varied types on bottom of dead coral-algal rock that is at places extensively veneered with coral-algal gravel and limesand. Dominant living coral types are Acropora, Porites, Orbicella, and meandriform genera. Heads of coralline algae and pavement-type corallines locally abundant. Depths less than 1 fathom at low tide.

Heliopora flats. Living Heliopora scattered over and rising 1 to 2 feet above limesand bottom. Upper tips of Heliopora barely exposed at low tide. Minor gravel patches occur locally. The sea cucumber Holothuria atra Jager is common. Echinoids recorded include a large poisonous Diadema and the harmless Tripneustes cf. T. gratilla.

Decadent _Heliopora flats_. Includes scraggly truncated _Heliopora_, a few other species of coral, and green algae, interspersed on surface of limesand and gravel.

_Dead Heliopora flats_. Elevated, truncated, dead Heliopora reef flats. Essentially the same as the foregoing, but inundated only at high tide and thus with no living _Heliopora_.

_Heliopora-Porites reef zone_. Living reef area, mainly _Heliopora_, in large flat-topped heads crusted with _Porites_ and crustose corallines.

_Sandy reef zone_. Mostly clean limesand with occasional living and dead coral at lagoonward margins of extensive leeward reef areas.

Intertidal to lagoonal environments

_Thalassia flats and shoals_. Dirty limesand with clusters or continuous mats of the turtle grass _Thalassia_. Commonly also with much of the green alga _Microdictyon_, the latter mostly unattached. The sea cucumber _Holothuria atra_ Jager is locally very abundant.

_Rocky flats and shoals_. Bottom mostly of dead coral-algal rock patchily veneered with gravel and sand. Scattered but fair representation of living coral dominated by stubbily branching _Acropora_ and _Pocillopora_ and locally by hassock-like _Porites_. Circular patches of the marine grass _Thalassia_ and the green alga _Microdictyon_ occur locally at the beachward margin in the inner lagoon, and the brown alga _Turbinaria_ is abundant at places. _Holothuria atra_ is locally abundant.

_Coralliferous rocky shoal bottom_. Bottom similar to that of "rocky flats and shoals," but with fairly abundant living coral patches wherein stubbily branching _Acropora_ and _Pocillopora_ are dominant.

Enclosed inlet. Area walled off as pair of fish ponds. Supports thick growth of turtle grass Thalassia and many fish, including small sharks and an unknown fish that is much feared by the natives (apparently not a barracuda, to judge from the description, but was not seen by our field party). This area was not explored or sounded, but it is reported by the native, Kane, to be generally under 4 feet and nowhere more than 9 feet deep at low tide.

### Environments of the lagoon and leeward shelf

The following units comprise a continuously variable sequence with more than usually indefinite boundaries:

Limesand bottom. Mostly clean limesand bottom at depths greater than 2 fathoms, living coral present locally.

Conspicuous lagoon patch reefs. Patch reefs of varied coral types and subordinate coralline algae, over 200 feet in diameter. Reef symbol on figure 2 used to indicate parts that are awash or nearly awash at low tide.

Limesand with scattered patch reefs. Mostly clean limesand floor, above which rise small scattered coral-algal patch reefs and pinnacles. Purely arbitrary and grades imperceptibly to limesand and patch reefs.

Limesand and patch reefs. Small patch reefs of varied coral types and subordinate coralline algae abundant but areally exceeded by limesand floor. Grades to "varied patch reefs and limesand," "Heliopora patch reefs and limesand," and "limesand with scattered patch reefs."

Varied patch reefs and limesand. Small patch reefs of varied coral types and subordinate coralline algae very abundant and only narrowly separated by areas of limesand floor.

Algal patch reefs and limesand. Abundant patch reefs of massive coralline algae and varied coral types presumably rising above limesand floor (bottom between reefs not observed or sampled).

Heliopora patch reefs and limesand. Abundant patch reefs consisting mainly of *Heliopora* in tree- and candelabra-like growths that produce a forest-like underwater scenery. In part the *Heliopora* patches are extensively masked by overgrowth of other coral types, and locally the patch reefs are of varied coral types. For the most part, intervening limesand bottom only narrowly separates individual patch reefs.

Varied bottom with scattered larger patch reefs. Subcircular patch reefs 100 to 300 feet in diameter scattered on bottom of limesand and limesilt with irregular low patches and small patch reefs of living coral and locally with abundant *Halimeda*. Depths between patch reefs mostly more than 3 fathoms, ranging to more than 7 fathoms locally. At shallow margin are several ridge-like patch reefs up to half a mile long.

Coral plantations. Coral and subordinate coralline algae essentially continuous or intimately intermingled with areas of dead coral on irregular bottom. *Acropora* the dominant genus in areas observed.

Limesand patches in coral plantations. Extensive areas of limesand and minor patches of coral within coral plantations.

## REFERENCES


Agassiz, Alexander, 1903, The coral reefs of the tropical Pacific, Mus. Comp. Zool. Mem., vol. 28, 410 pp.

British Colonial Office, 1950, Report on the Gilbert and Ellice Islands Colony for the year 1949, B. C. O., London, 52 pp.

Carey, L. R., 1918, The Gorgonaceae as a factor in the formation of coral reefs: Carnegie Inst., Dept. Marine Biol., vol. 9, pp. 341-362, pls. 100-105.

Carey, L. R., 1931, Studies on the coral reefs of Tutuila, American Samoa, with special reference to the Alcyonaria: Carnegie Inst., Papers from Tortugas Lab., vol. 27, pp. 53-98, figs. 1-14, pls. 1-7.

Couthouy, J. P., 1844, Remarks upon coral formations in the Pacific; with suggestions as to the causes of their absence in the same parallels of latitude on the coast of South America: Boston Soc. Nat. History Journ., vol. 4, pp. 66-105, 137-162.

Daly, R. A., 1920, A general sinking of sea-level in recent time: Nat. Acad. Sci. Proc., vol. 6, no. 5, pp. 246-250.

____________, 1926, Our mobile earth, Chas. Scribner's Sons, N. Y., 342 pp.

Dana, J. D., 1872, Corals and coral islands, Sampson Low & Co., London, 398 pp.

David, T. W. E., and Sweet, G., 1904, The geology of Funafuti: Royal Soc. London, Rept. of Coral Reef Comm., The Atoll of Funafuti, sec. 5, pp. 61-124, pls. B-E in text, pls. 1-19 in separate portfolio.

Emery, K. O., 1946, Marine solution basins: Jour. Geology, vol. 54, no. 4, pp. 209-228, figs. 1-15.

Finckh, A. E., 1904, Biology of the reef-forming organisms at Funafuti Atoll: Royal Soc. London, Rept. of Coral Reef Comm., The atoll of Funafuti, sec. 6, pp. 125-150, fig. 19.

Freeman, O. W., et al., 1951, Geography of the Pacific, John Wiley & Sons, Inc., N.Y.; Chapman & Hall, Ltd., London, 573 pp.

Kuenen, P. H., 1933, Geology of coral reefs: The Snellius Exped. (Eastern Neth. E. Ind. 1929-30), vol. 5 (Geol. Results), pt. 2, pp. 1-125, figs. 1-106, pls, 1-11, Kemink En Zoon, N. V. Utrecht.

Ladd, H. S., et al., 1950, Organic growth and sedimentation on an atoll: Jour. Geology, vol. 58, no. 4, pp. 410-425, figs. 1-2, pls. 1-7.

Newell, N. D., et al., 1951, Shoal-water geology and environments, eastern Andros Island, Bahamas: Am. Mus. Nat. History Bull., vol. 97, art. 1, pp. 1-29, figs. 1-5, pls. 1-8.

Pacific Sci. Board, 1951, Handbook for atoll research: mimeographed, numerous small units by various authors, Nat. Res. Council, Washington, D. C.

Safford, W. E., 1905, The useful plants of the island of Guam: U. S. Nat. Mus., Contrib. from U. S. Nat. Herbarium, vol. 9, 416 pp.

Setchell, W. A., 1928, A botanical view of coral reefs, especially of those of the Indo-Pacific region: Third Pan-Pacific Sci. Congress, vol. 2, pp. 1837-1843.

Sewell, R. B. S., 1936a, An account of Addu Atoll: British Mus. (Nat. Hist.), The John Murray Exped. 1933-34, Sci. Repts., vol. 1, no. 3, pp. 63-93, fig. 1, pls. 1-8.

Sewell, R. B. S., 1936b, An account of Horsburgh or Goifurfehendu Atoll: British Mus. (Nat. Hist.), The John Murray Exped. 1933-34, Sci. Repts., Vol. 1, no. 55, pp. 109-125, fig. 1, pls. 1-6.

Sollas, W. J., et al., 1904, The Atoll of Funafuti: Royal Soc. London, Rept. of the Coral Reef Committee, Harrison & Sons, London, 428 pp., 19 pls. in separate portfolio.

Stearns, H. T., 1941, Shore benches on North Pacific islands: Geol. Soc. America Bull., vol. 52, no. 6, pp. 773-780, figs. 1-2, pls. 1-3.

_____________, 1945, Eustatic shore lines in the Pacific: Geol. Soc. America Bull., vol. 56, pp. 1071-1078.

Tracey, J. I., Ladd, H. S., and Hoffmeister, J. E., 1948, Reefs of Bikini, Marshall Islands: Geol. Soc. America Bull., vol. 59, pp. 861-878, figs. 1-8, pls. 1-11.

U. S. Coast and Geodetic Survey, 1951, Tide tables, central and western Pacific Ocean and Indian Ocean: U. S. Dept. Commerce, Coast and Geodetic Survey, Washington, D. C., 343 pp.

U. S. Hydrographic Office, 1940, Sailing directions for the Pacific Islands, Vol. II: U. S. Navy Dept., Hydrographic Office Pub. No. 166 (Onotoa, p. 380), 522 pp.

U. S. Hydrographic Office, 1950, Supplement to Hydrographic Office Pub. No. 166, U. S. Navy Dept., Hydrographic Office Pub. No. 166, U. S. Navy Dept., Hydrographic Office Pub. No. 166-S, 85 pp.

Wells, J. W., 1951, The coral reefs of Arno Atoll, Marshall Islands, Nat. Res. Council, Pac. Sci. Bd., Atoll Res. Bull. No. 9, 14 pp., 16 figs.

Wentworth, C. K., 1947, Factors in the behavior of ground water in a Ghyben-Herzberg system: Pacific Sci., vol. 1, no. 3, pp. 172-184, figs. 1-4.